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DETERMINING THE AREA OF REVIEW FOR INDUSTRIAL WASTE DISPOSAL WELLS

BY

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REPORT

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S. Barker

University of Texas
Austin, Texas

October, 1981

Abstract

The area of review is defined by the radial distance from waste disposal wells in which the injection formation fluid pressure increases sufficiently to force formation fluids and/or injected wastes up abandoned well bores to contaminate underground sources of drinking water. The cost of corrective action required to prevent such contamination within the area of review can be considerable. To minimize the costs associated with subsurface disposal operations an appropriate area of reveiw must be adequately defined. This report provides a simplified procedure which can be utilized to determine a minimum area of review which can be safely applied to a given subsurface injection operation.

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CHAPTER I
INTRODUCTION

Introduction

The increased fluid pressure in a disposal zone which results from a waste injection operation may force injected and/or formation fluid to migrate up an abandoned well bore which penetrates the injection formation. Should migration occur, commingling with underground sources of drinking water may result. When a waste injection well reaches its design life (typically twenty years) the radial distance form the injector at which the potential for fresh water contamination exists is defined as the area of review. Environmental regulations require the well operator to take corrective action, as required, at each abandoned well within the area of review to insure that contamination does not occur. The cost of corrective action can be significant. Therefore, it is essential that the area of review be adequately defined before corrective measures are undertaken. This paper presents a simplified procedure which can be utilized to calculate the area of review.

If an abandoned well was not produced, drilling mud remains in the well bore since it has no means of escape. To evaluate the potential for fluid migration up

such a well bore the forces which act on this static mud column within the well bore must be determined. In most cases the wells were drilled with water base drilling muds which develop a gel structure when allowed to remain quiescent. To initiate flow up the abandoned well bore the fluid pressure in the formation must exceed the sum of the static mud column pressure (Ps) and the gel strength pressure (Pg). The area of review is defined as that area within which the well life formation pressure (P_f) is greater than (P_s) + (P_g).

Theoretical Development

Figure (1) represents a vertical force diagram of the static mud column in an abandoned well bore. The equation for the force balance takes the following form,

$$w + 2\pi\ r_w hGS = P_f\ \ \pi r_w^2 - P_t\ \pi r_w^2 \qquad (1\text{-}1)$$

simplify and let $r_w = \frac{D}{2}$, equation 1-1 becomes

$$P_f - P_t = 0.052 \rho h + \frac{4hGS}{D} \qquad (1\text{-}2)$$

neglecting surface pressure (P_t) and converting to consistent field units,

$$P_f = 0.052\ \rho_{min}\ h + 3.33 \times 10^{-3}\ \frac{Gsh}{D_{max}} \qquad (1\text{-}3)$$

Where: $P_s = 0.052\ \rho_{min} h$ -- represents the static mud column pressure

$P_g = 3.33 \times 10^{-3}\ \frac{Gsh}{D_{max}}$ -- represents the gel strength pressure

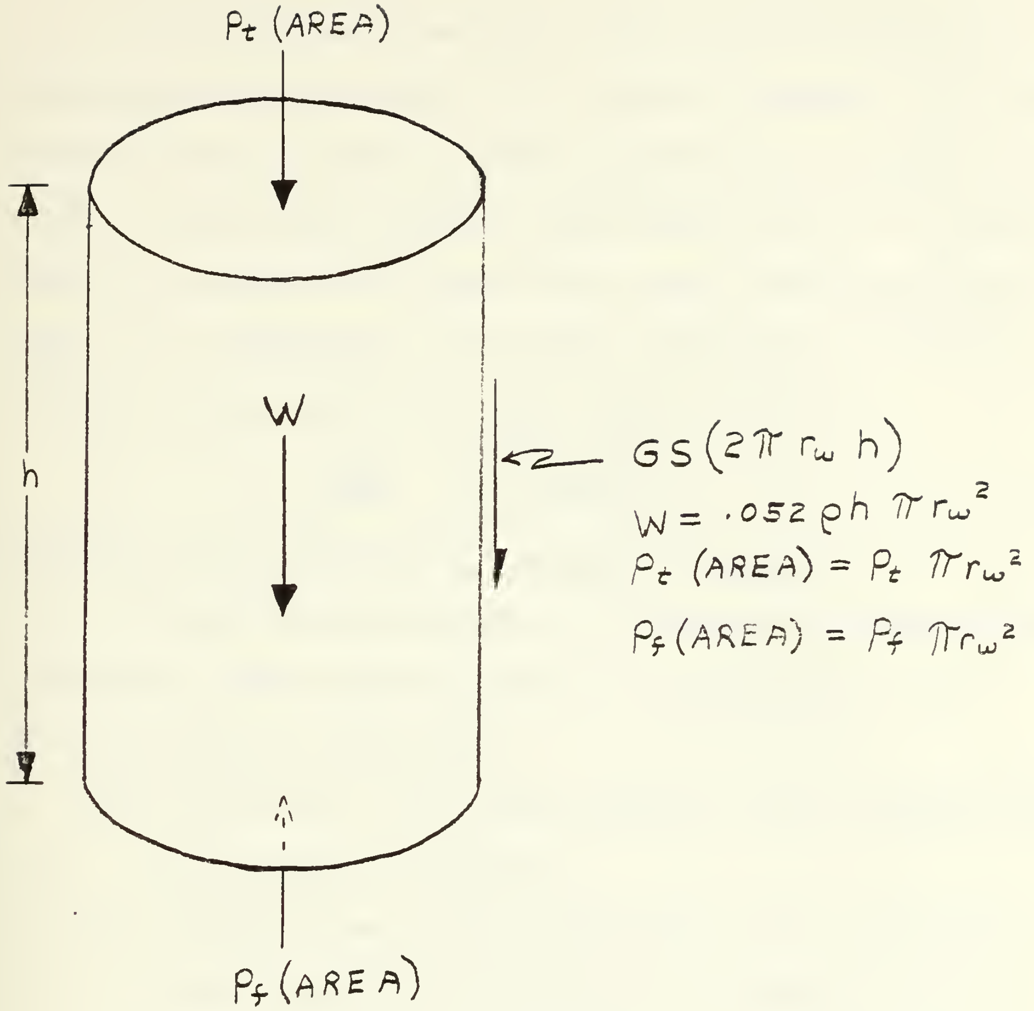

P_t (AREA)
h
W
$GS(2\pi r_w h)$
$W = .052 \rho h \pi r_w^2$
P_t (AREA) $= P_t \pi r_w^2$
P_f (AREA) $= P_f \pi r_w^2$
P_f (AREA)

FIGURE 1
STATIC MUD COLUMN
FORCE BALANCE DIAGRAM

P_f represents the well life formation pressure. The pressure which results at a radial distance r from the injection well at time t after the start of injection of a waste of small and constant compressibility at a constant rate Q throughout the life of the well into an infinite, isotropic, homogeneous, horizontal reservoir of uniform thickness and porosity is well approximated by,

$$P_f = Pi - \frac{QuB}{4\pi kh} E_i \left(\frac{-\phi ucr^2}{4kt} \right) \quad (1\text{-}4)$$

Procedure for Determining The Area of Review

The proposed procedure for determining the area of review for waste injection wells is predicated on the following basic assumptions:

1.) The static mud column extends to the surface and is uniform in density.

2.) Abandoned well bore diameters used in calculations are equal to the bit diameter plus two inches where bit refers to that used to drill the hole at the depth of the injection formation.

3.) The gel strength applied to all wells is 20 lbs/100 ft.^{2}

4.) Injection pressures will not exceed the fracture pressure of the injection formation.

5.) Known abandoned wells for which no data are available will be assigned the minimun mud density and the largest bit diameter noted for all

wells within a 2½ mile radius of the injector.

6.) None of the abandoned wells were completed and produced.

7.) All pressures are calculated at the top of the injection formation.

8.) All abandoned wells were drilled with water base muds.

9.) None of the abandoned wells are plugged.

Utilizing the developed theory and applying the basic assumptions, it is possible to compare P_f with $P_s + P_g$. The area of review will be defined by the radial distance from the injection well at which $P_f > P_s + P_g$.

The procedure employs an iterative process to determine the appropriate area of review for a given injection operation. The first iteration considers all abandoned wells within a 2½ mile radius of the injection wells. Once an area of review is determined, the process is repeated considering only those wells within the determined area of review. The iterative process is repeated until both the minimum mud density (ρmin) and maximum bit diameter at the depth of the injection formation (Dmax) for the abandoned wells within the previously defined area of review no longer vary with the iterations. When ρmin and Dmax stabilize the resulting area of review is the true area of review for the specified injection operation. The procedure is demonstrated by the following example.

Example

An industrial waste injection operation is proposed to dispose of 500 gal/min of waste for a period of 20 years. The waste will be injected into a sand formation at a depth of 5000 ft. employing two injection wells each operating at a rate of 250 gal/min. Figure (2) displays the abandoned well locations with respect to the injection wells. The mud densities and bit diameters for all abandoned wells are as noted in Table 1. The pertinent formation and fluid characteristics for the proposed operation are presented in Figure (3).

By means of a digital computer it is possible to use the developed theory to plot P_f, P_s, and $P_s + P_g$ as a function of the radial distance from the injection well as shown in Figure (3). The area of review is indicated by the radial distance from the injector at which the well life formation pressure intersects the constant pressure line $P_s + P_g$. For injection operations which utilize multiple injectors at a single site, the total flow of the wells can be input as one well and the area of review adequately approximated as that of a single well. Likewise, for wells of variable flow rate, an average, constant flow rate can be utilized to obtain satisfactory approximate results. P_g is calculated by using the largest bit diameter noted on well logs for all abandoned wells within a radial distance of 2½ miles of the injectors.

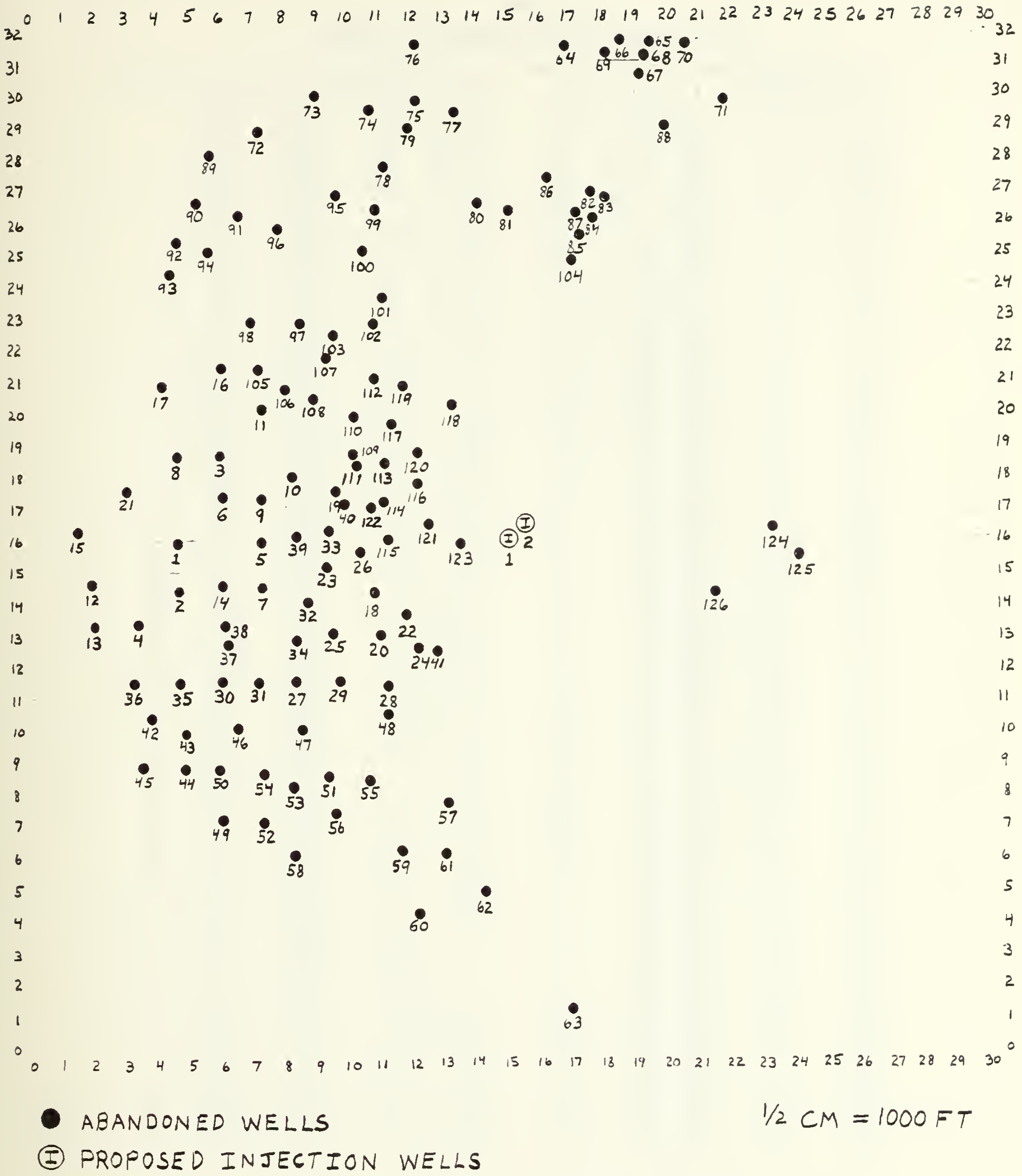


FIGURE 2. Abandoned and injection well locations

TABLE 1

INFORMATION PERTINENT TO EACH ABANDONED WELL

WELL #	X-CORD	Y-CORD	DENSITY lb/gal	BIT DIA in
1	4650	15900	9.4	7.875
2	4700	14550	10.5	7.875
3	5925	18600	10.5	7.875
4	3375	13275	10.5	71875
5	7350	15900	10.7	7.875
6	6025	17350	11.8	7.875
7	7375	14500	10.7	8.75
8	4575	18600	10.7	7.875
9	7350	17350	10.7	7.875
10	8300	17950	10.6	7.875
11	7325	20075	10.6	7.875
12	1950	14600	10.6	7.875
13	2000	13250	10.6	8.75
14	6050	14550	10.8	7.875
15	1525	16375	10.7	7.875
16	6050	21275	10.6	7.875
17	4175	20850	10.1	6.5
18	10800	14300	12.9	6.75
19	9600	17550	10.6	7.875
20	10950	12950	12.5	7.875
21	3050	17475	10.5	7.875
22	11825	13650	12.4	7.875
23	9350	15100	10.7	7.875
24	12150	12600	12.7	7.875
25	9525	13075	11.5	7.875
26	10450	15600	10.1	7.875
27	8400	11575	10.7	7.875
28	11225	11400	10.4	8.75
29	9700	11600	9.5	8.75
30	6000	11500	9.5	7.875
31	7250	11500	9.8	7.875
32	8750	14000	9.6	7.875
33	9400	16275	9.7	7.875
34	8400	12800	9.5	7.875
35	4675	11475	10.0	7.875
36	3300	11500	9.7	7.875
37	6150	12725	9.7	9.75
38	6100	13225	9.8	7.875
39	8400	16100	9.4	7.875
40	9825	17100	9.5	7.875
41	12700	12450	13.4	7.875
42	3800	10350	10.1	7.875
43	4850	9875	10.5	7.875
44	4850	8800	10.5	7.875
45	3550	8775	10.6	7.875
46	6450	10075	9.8	7.875
47	8525	10050	10.3	7.875
48	11200	10500	12.5	7.875
49	5950	7200	10.1	7.875
50	5800	8800	9.4	7.875
51	9300	8650	11.0	8.75
52	7325	7075	11.0	8.75
53	8250	8150	10.1	8.75
54	7150	8650	9.5	8.75
55	10650	8375	9.7	7.875
56	9550	7450	9.4	7.875
57	13000	7600	10.1	7.875
58	8275	6075	10.2	7.875
59	11650	6175	9.8	7.875
60	12100	4175	10.5	7.875
61	12975	6150	10.3	7.875
62	14250	4875	10.1	7.875
63	16850	1325	10.5	7.875
64	16850	31500	11.0	8.75
65	19500	31650	10.9	7.625
66	18700	31650	10.5	9.875
67	19200	30500	10.5	9.875
68	19400	31100	10.2	9.875
69	18100	31200	10.2	7.875
70	20600	31550	12.1	9.875
71	21750	29700	10.7	8.75
72	7350	28800	17.0	8.50
73	9000	29900	10.7	8.625
74	10750	29400	10.4	9.875
75	12200	29750	10.0	7.875
76	12250	31500	10.1	7.875
77	13400	29400	11.0	8.75
78	11250	27650	10.0	7.875
79	11900	28850	10.4	7.875
80	14100	26600	10.4	7.875
81	15100	26400	9.9	9.875
82	17650	26850	10.6	8.75
83	18025	26700	10.3	9.875
84	17700	26075	10.3	9.875
85	17225	25475	10.3	8.75
86	16300	27275	10.5	7.625
87	17200	26200	10.1	7.875
88	19925	28975	10.3	9.625
89	5700	28075	11.2	7.875
90	5325	26600	10.1	7.875
91	6650	26200	10.2	8.75
92	4725	25325	9.9	7.875
93	4525	24375	10.2	8.75
94	5600	25000	10.8	8.625
95	9625	26825	10.5	7.875
96	7775	25800	10.5	8.75
97	8450	22775	10.4	7.875
98	6975	22800	10.5	7.875
99	10875	26400	10.2	7.875
100	10450	25025	10.3	7.875
101	11075	23575	10.8	7.875
102	10775	22700	10.5	7.875
103	9550	22375	10.5	7.875
104	17000	24750	10.7	9.875
105	7175	21350	10.6	7.875
106	8000	20675	10.7	7.875
107	9200	21675	10.8	7.875
108	8875	20425	10.6	7.875
109	10100	18650	10.9	7.875
110	10175	19850	11.1	7.875
111	10150	18400	11.0	7.875
112	10825	21000	10.5	7.875
113	11100	18350	10.5	7.875
114	11200	17150	11.6	7.875
115	11325	15975	11.5	7.875
116	12225	17750	11.0	7.875
117	11425	19600	11.1	7.875
118	13325	20125	11.2	7.875
119	11700	20750	9.7	7.875
120	12250	18700	9.7	7.875
121	12450	16500	9.5	7.875
122	10700	17000	9.7	7.875
123	13475	15800	11.6	7.875
124	23300	16250	10.5	7.875
125	24050	15475	10.6	8.75
126	21550	14325	10.2	7.875

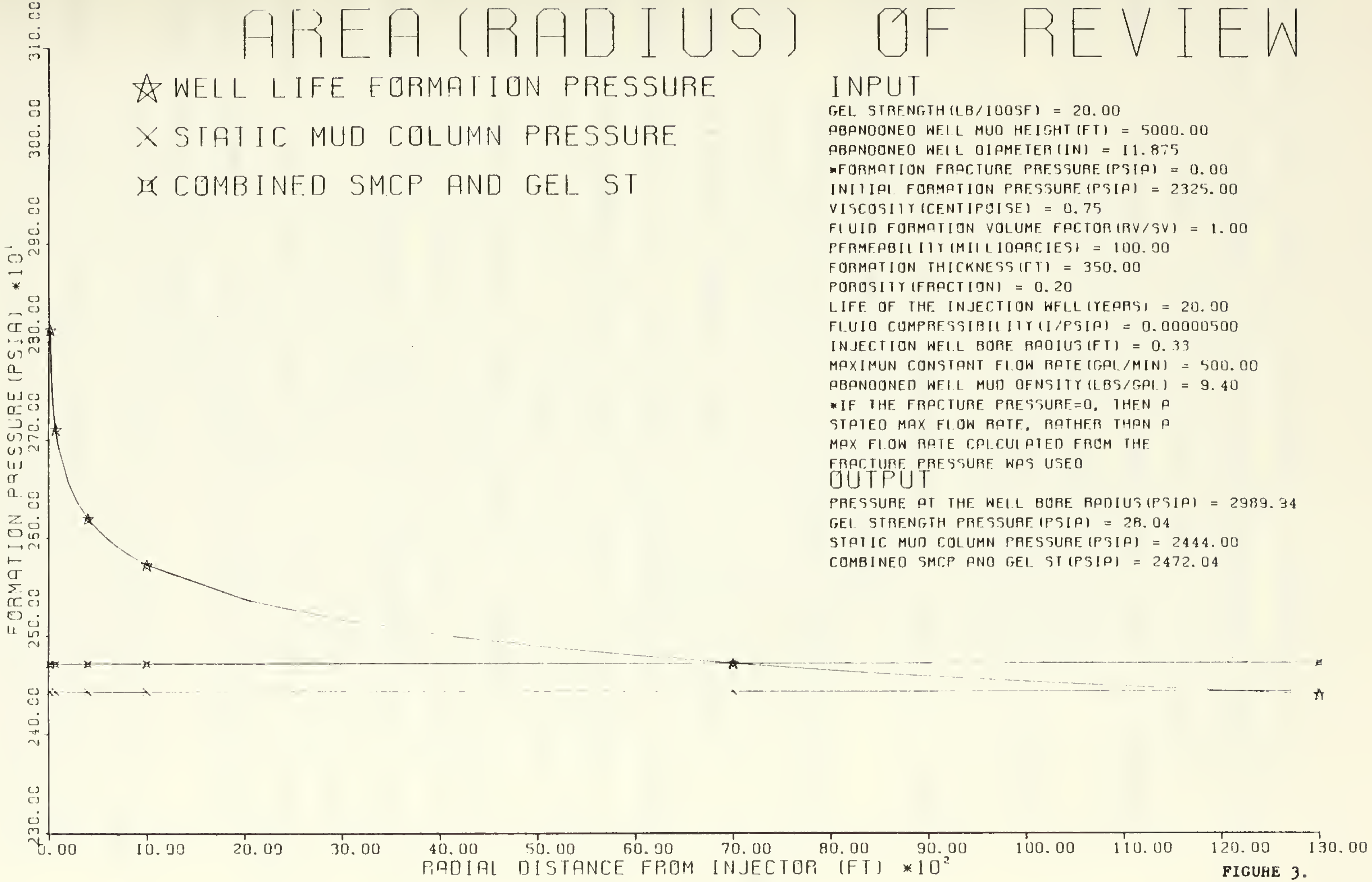

AREA (RADIUS) ØF REVIEW
☆ WELL LIFE FØRMATIØN PRESSURE
× STATIC MUD CØLUMN PRESSURE
⌘ CØMBINED SMCP AND GEL ST
INPUT
GEL STRENGTH(LB/100SF) = 20.00
ABANDONED WELL MUD HEIGHT(FT) = 5000.00
ABANDONED WELL DIAMETER(IN) = 11.875
*FORMATION FRACTURE PRESSURE(PSIA) = 0.00
INITIAL FORMATION PRESSURE(PSIA) = 2325.00
VISCOSITY(CENTIPOISE) = 0.75
FLUID FORMATION VOLUME FACTOR(RV/SV) = 1.00
PERMEABILITY(MILLIDARCIES) = 100.00
FORMATION THICKNESS(FT) = 350.00
POROSITY(FRACTION) = 0.20
LIFE OF THE INJECTION WELL(YEARS) = 20.00
FLUID COMPRESSIBILITY(1/PSIA) = 0.00000500
INJECTION WELL BORE RADIUS(FT) = 0.33
MAXIMUN CONSTANT FLOW RATE(GAL/MIN) = 500.00
ABANDONED WELL MUD DENSITY(LBS/GAL) = 9.40
*IF THE FRACTURE PRESSURE=0, THEN A
STATED MAX FLOW RATE, RATHER THAN A
MAX FLOW RATE CALCULATED FROM THE
FRACTURE PRESSURE WAS USED
OUTPUT
PRESSURE AT THE WELL BORE RADIUS(PSIA) = 2989.94
GEL STRENGTH PRESSURE(PSIA) = 28.04
STATIC MUD COLUMN PRESSURE(PSIA) = 2444.00
COMBINED SMCP AND GEL ST(PSIA) = 2472.04
FORMATION PRESSURE(PSIA) *10¹
310.00
300.00
290.00
280.00
270.00
260.00
250.00
240.00
230.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
110.00
120.00
130.00
RADIAL DISTANCE FROM INJECTOR (FT) *10²

FIGURE 3.

This provides a worst case design. Similarly, P_s is calculated utilizing the minimum mud density obtained from logs for the same radial distance from the injector. Figure (3) indicates the area of review for the example using these criteria as approximately 7000 ft.

Figure (4) is a computer generated plot which displays the location of the isobar on which $P_f = P_s + P_g$ and indicates those abandoned wells which lie within the area of review defined by the isobar.

Considering only the abandoned wells contained within the isobar defined in Figure (4), the area of review is recalculated. The new area of review, as noted in Figures (5) and (6), is an area encompassed by a radial distance of approximately 3800 ft from the injection wells which contains only 3 abandoned wells. It is noted that in the second iteration the minimum mud density (ρ_{min}) has increased from 9.4 to 9.5 lbs/gal and the maximum corrected bit diameter (D_{max}) has decreased from 11.875 in to 9.875 in. Another iteration of the procedure yields the same values for ρmin and D_{max}. Therefore, the area of review defined is the true area of review for the specified injection operation.

Corrective action must be considered for all wells within the area of review. Therefore, each of the three wells should be analyzed on an individual basis using the

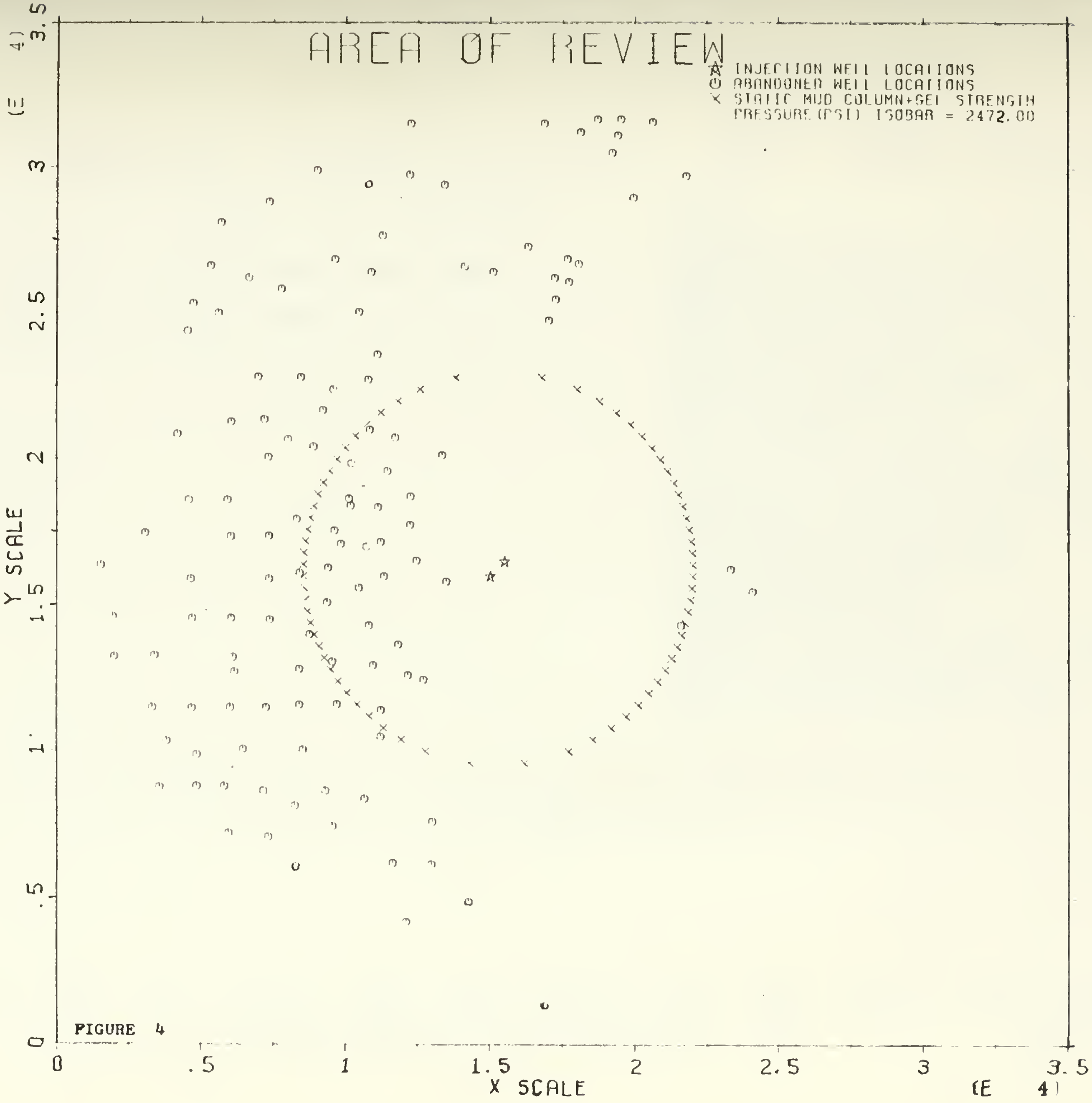
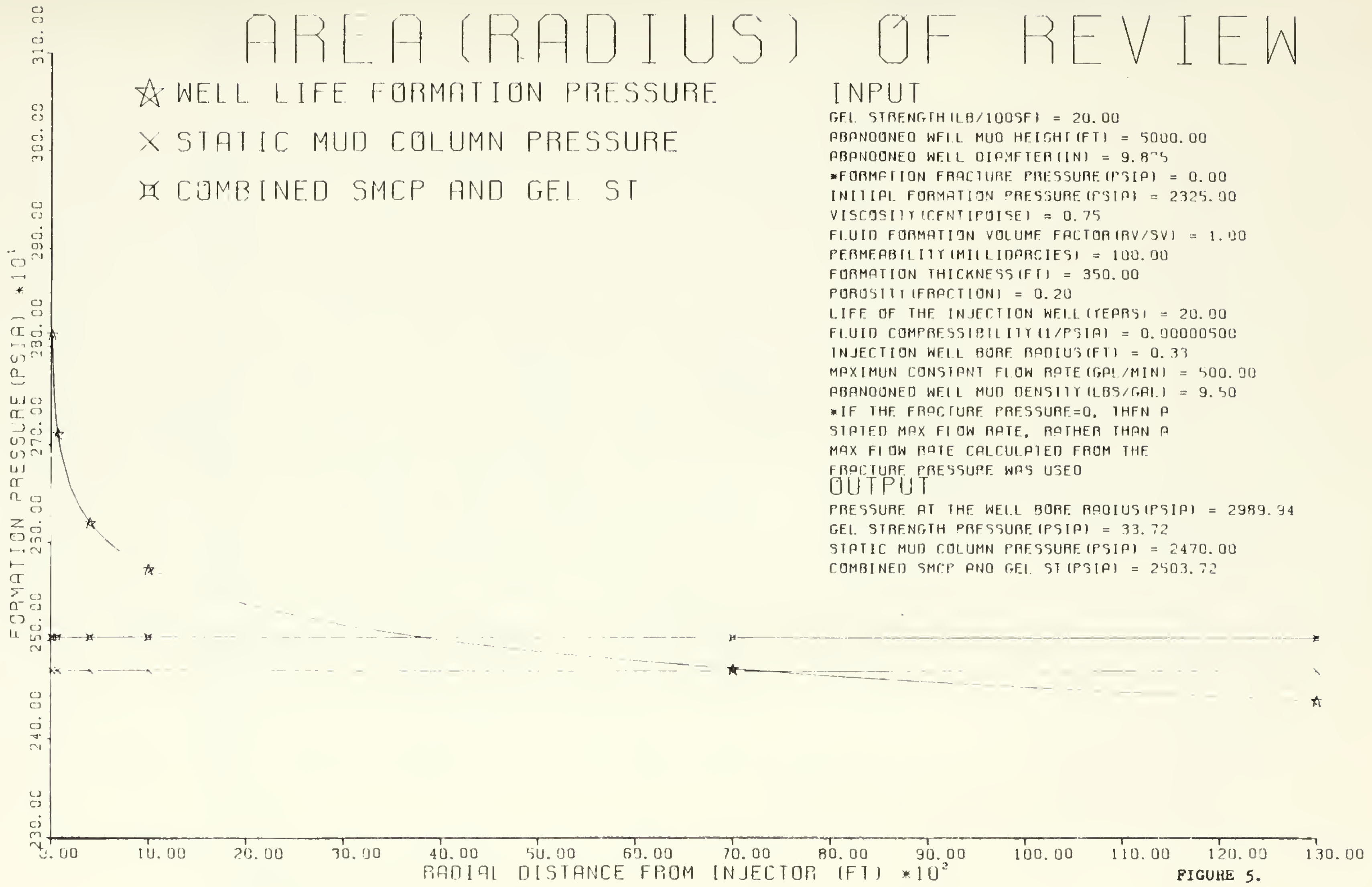

AREA ØF REVIEW
☆ INJECTION WELL LOCATIONS
⊙ ABANDONED WELL LOCATIONS
× STATIC MUD COLUMN+GEL STRENGTH
PRESSURE (PSI) ISOBAR = 2472.00
Y SCALE
(E 4)
0
.5
1.
1.5
2
2.5
3
3.5
X SCALE
0
.5
1
1.5
2
2.5
3
3.5
(E 4)

FIGURE 4



```
INPUT
GEL STRENGTH(LB/100SF) = 20.00
ABANDONED WELL MUD HEIGHT(FT) = 5000.00
ABANDONED WELL DIAMETER(IN) = 9.875
*FORMATION FRACTURE PRESSURE(PSIA) = 0.00
INITIAL FORMATION PRESSURE(PSIA) = 2325.00
VISCOSITY(CENTIPOISE) = 0.75
FLUID FORMATION VOLUME FACTOR(RV/SV) = 1.00
PERMEABILITY(MILLIDARCIES) = 100.00
FORMATION THICKNESS(FT) = 350.00
POROSITY(FRACTION) = 0.20
LIFE OF THE INJECTION WELL(YEARS) = 20.00
FLUID COMPRESSIBILITY(1/PSIA) = 0.00000500
INJECTION WELL BORE RADIUS(FT) = 0.33
MAXIMUN CONSTANT FLOW RATE(GAL/MIN) = 500.00
ABANDONED WELL MUD DENSITY(LBS/GAL) = 9.50
*IF THE FRACTURE PRESSURE=0, THEN A
STATED MAX FLOW RATE, RATHER THAN A
MAX FLOW RATE CALCULATED FROM THE
FRACTURE PRESSURE WAS USED
OUTPUT
PRESSURE AT THE WELL BORE RADIUS(PSIA) = 2989.94
GEL STRENGTH PRESSURE(PSIA) = 33.72
STATIC MUD COLUMN PRESSURE(PSIA) = 2470.00
COMBINED SMCP AND GEL ST(PSIA) = 2503.72
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FIGURE 5.

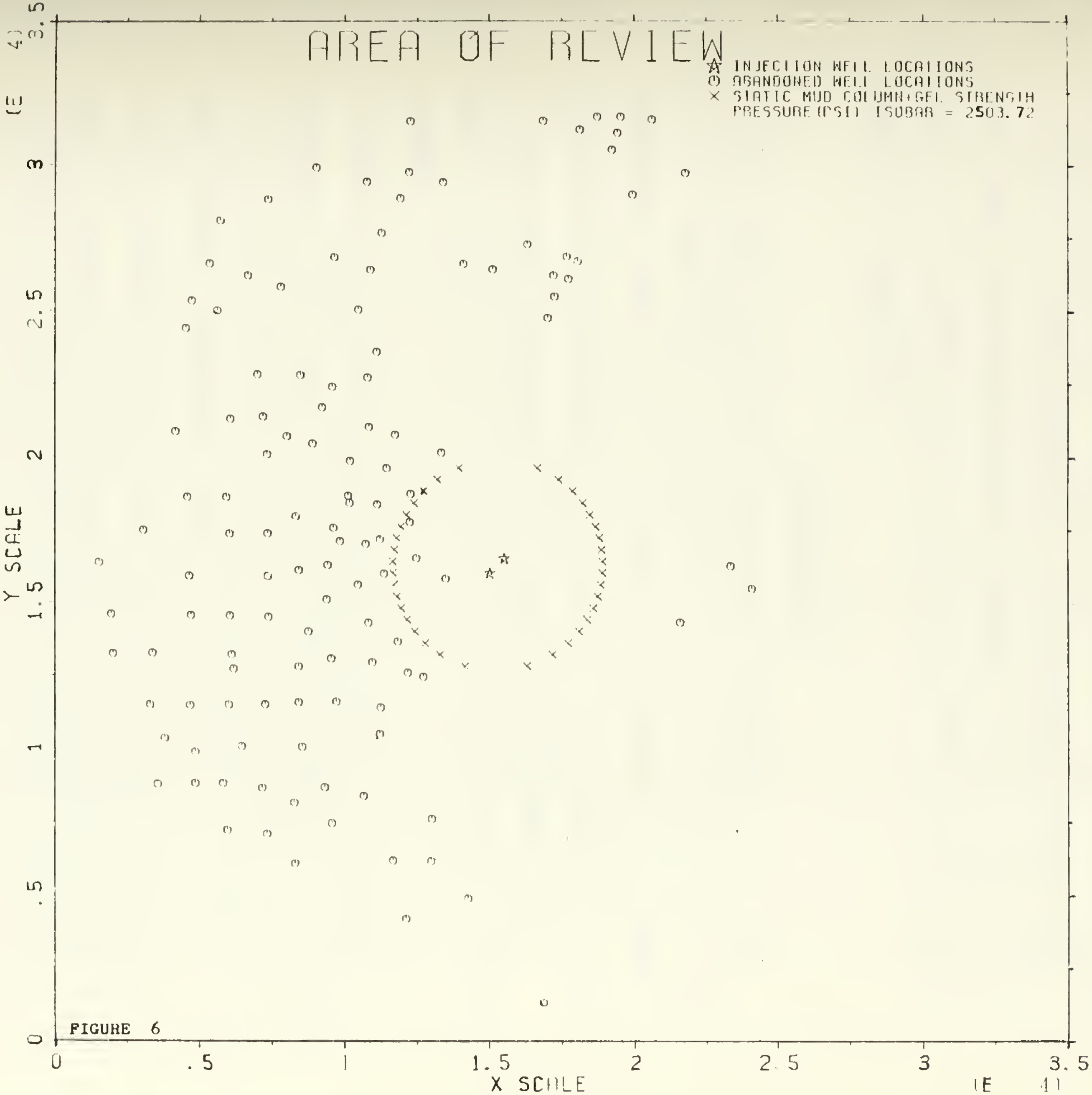
AREA ØF REVIEW
☆ INJECTION WELL LOCATIONS
⊖ ABANDONED WELL LOCATIONS
× STATIC MUD COLUMN+GEL STRENGTH
PRESSURE (PSI) ISOBAR = 2503.72
Y SCALE
(E 4)
0
.5
1
1.5
2
2.5
3
3.5
X SCALE
(E 4)

FIGURE 6

developed theory. After individual analysis it is apparent that well number 121 is capable of allowing fluid to migrate up its well bore. If records indicate that well number 121 was properly plugged no corrective action would be required prior to conducting the proposed waste injection operation.

Conclusions

1. The costs associated with record searches and field surveys undertaken to determine the plugging history of abandoned wells can be avoided if the wells lie outside the area of review determined by the described procedure.
2. The costs associated with plugging abandoned wells located outside the calculated area of review can also be avoided.
3. Since the pressure cone resulting from the injection operation falls off quickly the size of the area of review is extremely sensitive to small pressure differences at large radial distances from the injector.
43. The number of abandoned wells which fall inside the area of review can be reduced by varying injection well locations, injection rates and the injection formation.

NOMENCLATURE

D - Diameter of the well bore (in)

Dmax - Maximum bit diameter (in)

GS - Gel strength (lbs/100 Ft^{2})

h - height of mud column (Ft)

r_w - well bore radius (in)

P_f - formation pressure (Psi)

P_g - gel strength pressure (Psi)

P_s - Static mud column pressure (Psi)

P_t - air pressure (Psi)

W - weight of the mud column (16s)

ρ - mud density (lbs/gal)

ρ_m - minimun mud density (lbs/gal)

CHAPTER II

BACKGROUND

The Environmental Atmosphere

The rapid rate of industrial developement that exists in a highly industrialized country like the United States has given birth to a myriad of environmental problems which resist time and linger to haunt man for decades. For example, the extensive use of polychlorinated biphenols (PCB's) as a cooling medium in electric transformers and capacitors presents a current problem which remains to be solved. The widespread use of PCB's has resulted in the distribution of millions of gallons of nonbiodegradeable, carcinogenic waste in transformers located in our factories, schools, office buildings, and neighborhoods. Many of the transformers are leaking and the public is unknowingly being exposed to the carcinogenic waste. Extensive use of the insecticide DDT and the insulating material asbestos has presented similar environmetnal hazards. An environmental dilemma exists in the case of PCB's and other hazardous wastes. Environmental groups have strongly opposed the establishment of hazardous waste disposal sites within their geographic area of interest. The proposed disposal sites would utilize advanced technology to provide the best

means of disposal presently available. Without the establishment of the needed waste disposal facilities the wastes will remain interdispersed throughout the populace where they pose a greater risk to man and the environment. It becomes apparent that the government, industry and the general public must cooperate and pool their resources if a logical and acceptable course of disposal action is to be pursued. The total dominance and influence of one interest group over another may destroy the balance required to allow growth and developement to continue while minimizing any adverse impact on the environment.

The well managed and organized efforts of environmentally conscious organizations have increased the public awareness of the dangers which result from the improper disposal of hazardous waste. These efforts and extensive media coverage of the environmental catastrophies resulting form the improper disposal of hazardous wastes (i. e. Love Canal in Niagara Falls, New York) have fueled the proliferation of federal, state and local regulations designed to protect man and the environment. These regulations, which govern all aspects of hazardous waste disposal, necessitate considerable capital investments by industry in their efforts to attain compliance. Although few can dispute the need to regulate hazardous waste disposal, some of the regulations promulgated towards this end can

be questioned. Some requirements appear to be predicated on political, social or historical preferences or practices, rather than evolving from sound engineering and scientific principals which provide a means of verification and/or justification. This approach has resulted in the unnecesssary expendature by industry of funds to gain compliance with the regulations.

The Goal of Industrial Waste Disposal Regulations

The primary goal of the hazardous waste regulations which govern the disposal of liquid hazardous waste is to protect underground sources of drinking water. The originators and enforcers of the regulations must not loose sight of this goal. The regulations should be enforced in a manner which allows the waste generator to utilize the most advanced waste disposal technology available if it can be demonstrated that the technology provides the best environmental alternative for disposal. When more than one disposal option can be pursued, the regulatory agencies should encourage the generator to pursue the best environmental option. The regulations should not be so restrictive that they eliminate the waste disposal option which presents the least potential for contamination of ground water sources of drinking water.

Liquid Waste Disposal Options

Biological Treatment, Incineration, Off-site Disposal, On-site Landfill, Surface Impoundment, and Subsurface Injection are liquid waste disposal options available to the waste generator. Surface impoundment (evaporation) is the most common and frequently utilized means of disposal for liquid hazardous waste. Annually, Texas generates and disposes of 13.3 billion gallons of industrial waste in surface impoundments.[1] Since few of the impoundments are lined, the potential for contamination of ground water sources of drinking water is high. Even those evaporation impoundments located on low permeability clays present a contamination risk since no natural material is impermeable. The cost of modifying existing impoundment facilities to eliminate the contamination risk and/or to comply with regulatory requirements is prohibitive. To eliminate the risk other sources of disposal must be pursued. A preliminary study of surface impoundments examined 85 case histories of ground water contamination resulting from surface impoundment.[2] The study emphasizes the risks that result from utilizing surface impoundment disposal methods.

To eliminate the contamination which is inherent with many of the existing surface impoundments it has become necessary to pursue alternate means of hazardous

waste disposal. A disposal means which has gained in popularity during the past four decades is the subsurface disposal of wastes by injection into subsurface formations containing salt water. Subsurface injection removes the waste from the biosphere and confines it in deep geologic formations. Since 1961 over 42 billion gallons of waste has been disposed of by subsurface injection in Texas alone.[1]

Summary

As of 1973, 20% of the total United States water needs have been fulfilled utilizing ground water. Ground water fulfills more than 85% of the public water needs in several states (Mississippi, Florida, New Mexico, Idaho and Hawaii).[3] This heavy dependance on ground water as a source of drinking water demands every effort to protect the remaining ground water aquifers from sources of contamination. Once the aquifer is contaminated, methods available to return it to an acceptable level of water quality are not presently economically feasible.[4]

Where geologic and engineering studies indicate that a prospective site is suitable for subsurface injection, this method of hazardous waste disposal should be pursued. Few cases of ground water contamination resulting from subsurface injection operations have been

documented. Technological advances and more restrictive waste injection regulations have virtually eliminated the potential sources of contamination which presented problems in the past. Subsurface injection has demonstrated itself to be an effective means of hazardous waste disposal. Regulatory actions that eliminate subsurface injection as a economical means of hazardous waste disposal will adversely effect the quality of ground water either directly or indirectly.

CHAPTER III

DETERMINING THE AREA OF REVIEW FOR INDUSTRIAL WASTE DISPOSAL WELLS

Introduction

During the course of the past four decades disposal of hazardous wastes by means of subsurface injection has emerged as an acceptable alternative to surface disposal methods. At present, subsurface injection is conducted at more than 300 industrial waste disposal wells located at several geologically favorable sites throughout the country. The largest concentration of industrial waste disposal wells is along the Gulf Coast of Texas. Figure (7). The majority of the wells inject waste into zones located below ground water sources of drinking water at depths between 3000 and 7500 feet. The disposal wells are designed to inject into sedimentary formations, approximately 62% of which are sand formations and 34% of which are limestone dolomite.[5] The sedimentary basins which provide deep reception formations containing brine may also contain shallower formations saturated with ground water suitable for drinking. Since most industrial sites are located within or near densely populated areas which may rely heavily upon undergroundd sources of drinking water, precautions must be taken to ensure that

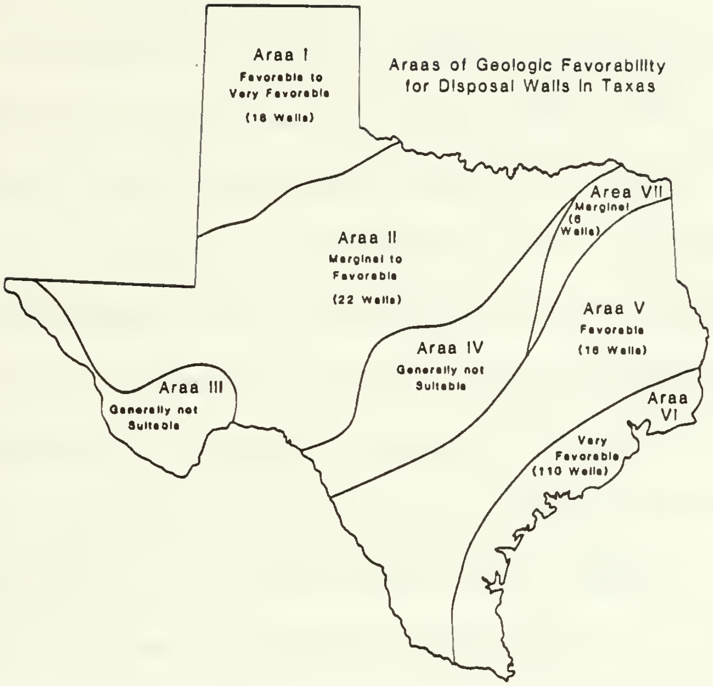

FIGURE 7. Location of waste disposal wells in Texas (From Kent[1])

the waste injection operations do not contaminate the overlying formations containing drinking water.

In compliance with the Safe Drinking Water Act,[6] The Environmental Protection Agency (EPA) has developed minimun requirements for state operated programs designed to regulate the subsurface disposal of industrial waste by injection. This effort is designed to protect underground sources of drinking water from endangerment resulting from underground injection operations. The technical criteria and standards for use by the states in the developement and implementation of their state Underground Injection Control (UIC) Programs were promulgated by the Federal Register on 24 June 1980.[7] Texas was the first state to have an injection well regulatory program and to a large extent the Federal UIC Program was patterned after the Texas guidelines. The Texas Department of Water Resources (TDWR) recently promulgated the Texas UIC program.[8] The program establishes the standards and technical criteria which will govern subsurface disposal of industrial waste in Texas. Appendix A discusses the standards and criteria establishes by the EPA and TDWR.

Several potential sources of groundwater contamination may develop during the life of an injection operation. Potential sources include: 1) failure of the injection well, 2) faults or fractured confining zone, and

3) upward migration of wastes via the abandoned well bores which penetrate the prospective injection zone. An adequate hydrogeologic survey should eliminate the possibility of injecting into excessively faulted zones and/or zones with fractured confining rock. Proper design, installation, maintainance and monitoring of the injection well will virtually eliminate the injector as a source of contamination. The potential for upward migration of waste via the abandoned well bores however, requires further investigation.

This report reviews the criteria which apply to contamination which may result from the migration of native formation fluid and/or injected waste up the abandoned well bore. A procedure is presented to determine which abandoned wells should be reviewed to determine if corrective action is necessary to prevent the contamination of ground water sources of drinking water which may result from upward migration in the abandoned well bore. The procedure is readily applicable in the Gulf Coast Area and can be adapted to other areas as required.

Criteria Which Apply to Abandoned Wells

Defining the Area of Review

The EPA and TDWR have promulgated regulations defining the area of review for an injection well or a group of wells.[7,8] The EPA defines the area of review to

be the zone of endangered influence or a radius of ¼ mile which ever is less. Where the zone of endangered influence is the area outlined by a radial sweep around an injection well, field or project where in the pressures in the injection zone may cause the migration of the injected and/or formation fluid into an underground source of drinking water. The computation of the zone of endangered influence may be based on appropriate equations for pressure calculations and/or models and shall be determined for the life of the injection well system. The TDWR defines the area of review for industrial waste disposal wells as a radius of 2½ miles or an area of lesser radius, if so determined by the TDWR. The minimun area of review allowed by the TDWR shall not be less than a ¼ mile radial distance from the injection well.

References (9) and (10) indicate that the TDWR utilized a formation pressure increase tolerance of .01 or .015 psi/ft at well depth to calculate the pressure resistance in an unplugged abandoned wells. If the formation pressure does not exceed the pressure increase tolerance at a given abandoned well then the area of review may be reduced to exclude that well. The tolerance does not consider the characteristics of the fluid which occupies the abandoned well bore.

Significance of the Area of Review

The significance of the area of review is that the regulations require wells within the area of review, which are not adequately plugged and which as a result of injection operations may cause contamination of subsurface sources of drinking water, to receive corrective action adequate to prevent such contaminaton as a condition of the underground injection operating permit.

The required corrective action is usually the plugging of the abandoned well with cement. Since plugging wells can represent an extensive capital investment, an adequate definition of the area of review becomes an important economic factor which must be considered when the waste injection feasibility study is conducted. If an area was fully developed as a result of oil and gas exploration the area defined by a 2½ mile radius would contain more than 300 wells. The cost of locating and plugging that number of wells would be prohibitive.

The Texas UIC regulations[8] require the subsurface disposal well permit applicant to submit a technical report with the application for permit. The information required in the technical report that relates to the area of review includes:

1) A map indicating the location of the proposed injection well and the applicable area of review. Within the area of review, the map must show the

number, or name and location of all producing wells, dry holes, surface bodies of water, springs, mines, quarries, water wells and other pertinent surface features including residences and roads;

2) A tabulation of reasonably available data on all wells within ½ mile of the injection well and all wells within the area of review which penetrate to within 300 feet of the injection zone. The data shall include a description of the type, construction date drilled, location depth, record of plugging and/or completion, and other information of each well as required;

3) Maps and cross-sections indicating the general vertical and lateral limits of those aquifers within the area of review that contain water with less than 3,000 mg/l Total Dissolved Solids (TDS) and those that contain water with less than 10,000 mg/l TDS, their positions relative to the injection formation and the direction of water movement, where known, in each fresh water aquifer which may be affected by the proposed injection.

The cost of obtaining and preparing the above required information could represent a significant percentage of the initial costs associated with the proposed subsurface waste disposal well. Thus the magnitude of the

effort required to prepare the permit application and technical report is controlled to a large degree by the determined area of review.

Theoretical Description of the Pressures Acting at the Abandoned Well Bore

Discussion

The vast majority of the artificial penetrations which intersect potential injection aquifers are the result of oil and gas exploration and developement. Therefore, it is logical to conclude that a means of adequately defining the area of review may lie in an understanding of the principals and practices which govern drilling and well completion operations.

The rotary drilling method is predominately utilized in the drilling of oil and gas exploration and development wells. This drilling method is dependant upon the use of a drilling fluid (mud) which performs several functions which are vital to the method. Appendix B provides a brief discussion of the importance of drilling fluid to the rotary drilling method. Upon completion of the drilling operation if the well is not completed for production, the drill string and bit are removed from the well bore. Drilling mud will remain in the well bore. Since no means of escape exists, provided lost circulation

zones were not encountered, the drilling mud used to drill the well will remain in the well bore indefinately.

Important Drilling Mud Characteristics

One of the primary functions of the drilling mud is the removal of bit cuttings during the drilling operation. The mud must remove the cuttings from beneath the bit, transport them up the well bore-drill pipe annulus and release them at the surface. During periods of suspended circulation, the primary mud property which acts to suspend the cuttings in the static mud column is the mud gel strength. The gel strength develops with time as the mud column remains quiescent. Since the bouyant force of a static fluid increases with density, drilling fluids of higher density are also capable of suspending cuttings during periods of non-circulation. The density of the mud also accomplishes another important function, that of controlling encountered formation pressures by providing a static mud column which is capable of exerting sufficient pressure to prevent the inflow of formation fluids into the well bore.

Pressures at the Well Bore

An abandoned well bore can be considered to exist in a static state. For a static state to exist the forces which act on the mud column must balance. Figure 1 represents a vertical force diagram of the static mud column in

an abandoned well bore. The equation for the force balance takes the following form,

$$w + 2\pi r_w h\ GS = P_f\ \pi r_w^2 - P_t\ \pi r_w^2 \qquad (1\text{-}1)$$

where $w = \pi r_w^2 \gamma h$

Simplifying the force balance results in the following pressure equation,

$$P_f = \gamma h + \frac{4hGS}{D} \qquad (3\text{-}1)$$

Pressure Generated by the Static Mud Column

The hydrostatic law of variance of pressure can be written in the form,

$$P = \gamma h \qquad (3\text{-}2)$$

Where: h denotes the height of the liquid column, ft P denotes the pressure at the base of the vertical liquid column of height h, lbs/ft^2

γ denotes the specific weight, lbs/ft^3

Equation 3-2 can be transformed into the following usable field equation:

$$P_s = 0.052\ \rho h \qquad (3\text{-}3)$$

Where: the contant 0.052 has the units gal/ft-in^2

ρ denotes the density of drilling mud, lbs/gal

h denotes the height of the

static mud column, ft

Ps denotes the static mud column pressure, psi

Pressure Required to Break the Gel Strength of the Static Mud Column and Initiate Flow

Most oil and gas wells are drilled utilizing water base drilling fluids. When these fluids remain in a quiescent state a gel structure developes. The strength of this structure is important since the formation pressure would have to increase sufficiently to shear this structure before the mud in the abandoned well will flow freely. Melrose, et al[11] defined the pressure gradient required to rupture the gel strength and initiate flow in a horizontal pipe as:

$$\frac{\Delta P}{h} = \frac{4GS}{D} \qquad (3\text{-}4)$$

Equation 3-4 can be converted to the following usable field equation:

$$Pg = 3.33 \times 10^{-3} \quad \frac{Gsh}{D} \qquad (3\text{-}5)$$

Where: The constant $3.33X10^{-3}$ has the units ft/in

h denotes the height of the static mud column, ft

GS denotes the gel strength of the drilling mud, lbs/100 ft^2 (Gel strength pressure, Psi)

D denotes the diameter of the abandoned

well bore, in Pg denotes the pressure required to break the gel structure and initiate flow in a horizontal pipe system where gravity effects are negligible

Formation Pressure Rise During Injection

The well life formation pressure (P_f) which results at a radial distance r from the injection well at time t after the start of injection of a small and constant compressible fluid at a constant rate Q throughout the life of the well into an infinite, isotropic, homogeneous, horizontal reservoir of uniform thickness and porosity is well approximated by, [12].

$$P_f(r,\ t) = Pi - \frac{QuB}{4\pi Kh}\ Ei\left(\frac{-\phi ucr^2}{4kt}\right) \qquad (3\text{-}6)$$

Appendix C provides a definition of the terms of equation 3-6 and demonstrates the derivation of the equation from the diffusivity equation.

Pressure Theory Summary

The area of review may theoretically be defined as the radial distance from an injection well where in:

The formation pressure is greater than the static mud column pressure + the gel strength pressure of the static mud column which occupies the abandoned well bore

$$P_f > P_s + P_g \qquad (3\text{-}7)$$

Field Procedure for Determining the Area of Review

Introduction

This section of the report promulgates a general procedure which can be utilized to determine the area of review for a proposed subsurface injection disposal operation. The procedure employs the developed theory to determine which abandoned wells must be reviewed to determine if corrective action is required. The corrective action is required to prevent the contamination of underground sources of drinking water which could result from the migration of waste and/or formation fluid up the abandoned well bore. Application of the procedure during the initial planning stages of a proposed injection operation could play an important role in the decision making process. The variations and options provided by the procedure will allow planners the flexibility of varing the injection rates, well locations and other pertinent factors to insure that the required injection operation can be accomplished without the expenditure of funds to physically locate and/or correct abandoned wells unnecessarily.

Assumptions

1.) The static mud column extends to the surface and is uniform in density.

2.) Abandoned well bore diameters used in calculations are equal to the bit diameter plus two

inches where bit refers to that used to drill the hole at the depth of the injection formation.

3.) The gel strength applied to all wells is 20 lbs/100 Ft^2

4.) Injection pressures will not exceed the fracture pressure of the injection formation.

5.) Known abandoned wells for which no data are available will be assigned the minimum mud density and the largest bit diameter noted for all wells within a 2½ mile radius of the injector.

6.) None of the abandoned wells were completed and produced.

7.) All pressures are calculated at the top of the injection formation.

8.) All abandoned wells were drilled with water base muds. (fresh water, salt water, oil-in-water emulsions and surfactant muds).

9.) None of the abandoned wells were plugged.

Justification of Assumptions

1.) Upon entering some abandoned wells it has been noted that segregation of the mud components does occur with time. A sedimentary process apparently occurs to some degree within the static mud column. Data describing the degree to which sedimentation occurs is not readily

available since the phenomenon has received little attention. If segregation of the mud column occurs the mud density will increase with depth. The actual characteristics of the density gradient is not known since it would vary with the mud type, composition and the characteristics of the formation drilled. Since the mud has no means of escape from the well bore the assumption that the mud column has a constant density with depths should result in the calculation of a static mud colum pressure at the depths of concern which varies little, if at all, from the actual pressure. Here again the gel structure would be expected to increase with depth because of the deposition of the gel producing particles at the lower portion of the well bore. The assumption of uniform mud consistency provides the only means of calculating the gel strength pressure since the variations of gel strength with mud segregation in abandoned wells are not known.

2.) The gel strength pressure (Pg) is inversely proportioned to the well bore diameter, therefore to compensate for the larger surface casing the effective diameter of the abandoned well bore will be the bit diameter used to drill the hole

at the depth of the injection formation plus two inches.

3.) The justification for selecting 20 lbs/100 Ft^2 as the expected minimun gel strength for all water base muds is discussed in Appendix D.

6.) If an abandoned well was completed and produced the fluid occupying the well bore will be a light fluid without gel strength and the procedure described here would not apply.

8.) Because of the lack of gel strength associated with oil-base, air and gas drilling fluids wells drilled or completed with these fluids should be evaluated by alternate procedures.

9.) Considering all wells to be unplugged allows the pressure calculations to be conducted on the static mud column in each abandoned well bore in an equitable manner for all wells.

Example

Appendix E is an example which correlates with the procedural steps presented below. The example represents a two well injection system which is injecting into a zone with characteristics selected to emphasize the procedure. The abandoned wells represent an actual field orientation and the mud densities and bit sizes utilized were obtained from the well logs for the various wells.

Step 1

The first step in the procedure is obtaining the information required to calculate the pressures. Table 2 lists the subsurface information required and the means by which it can be evaluated. An effort to attain well logs for all abandoned wells within a 2½ mile radius of the proposed injection well or wells should ensue. The appropriate state regulatory agency for oil and gas exploration should be contacted for assistance in obtaining well logs or a commercial log library can be contacted.

Step 2

Upon completion of a thorough investigation to locate all abandoned wells within the 2½ mile radius of the injectors, the abandoned well locations should be accurately indicated on a suitable map. An appropriate grid system which indicates the distance, in feet between the abandoned wells should then be superimposed over the map. The grid system provides a means by which the relative distance between the abandoned wells and the injection wells can be determined so that the pressures resulting from the injection operation can be evaluated at each abandoned well.

TABLE 2.

SUBSURFACE INFORMATION REQUIRED FOR PRESSURE CALCULATIONS

PRESSURE CALCULATED	INFORMATION DESIRED	METHODS AVAILABLE FOR EVALUATION
Formation	Porosity	Core analysis, electric, sonic and radioactive logs
	Permeability	core analysis, buildup, drawdown or injectivity tests or electric logs
	Formation fluid pressure	Drill stem test, hydrostatic pressure gradient, pressure bomb
	Formation thickness	electric logs, sonic logs, radioactive logs
	Formation depth	electric, sonic and radioactive logs
Static mud column	Mud density	well log headers
	Formation depth	(same as above)
Gel strength	Bit size	well log headers
	Formation depth	(same as above)

Step 3

Utilizing the information gathered in step one, the formation, static mud column, and gel strength pressures are calculated. The formation pressure calculated must represent the injection formation pressure at the end of the stated life of the injection well system. A computer program INJWEL (Appendix F) was developed to calculate the required pressures. Use of the program is demonstrated in the example contained in Appendix E. The program calculates the formation pressure, static mud column, and gel strength pressures up to a radial distance of 13,000 feet (approx. 2½ miles) from the injector. The program also generates an X-Y Plot of the formation, static mud column, and static mud column + gel strength pressures as a function of the radial distance from the injection well. The x-y Plot graphically approximates the area of review by indicating the radial distance from the injector where the static mud column + gel strength pressure exceed the formation pressure. Since most waste injection operations utilize more than one injection well the program can be used in these instances by assuming that the combined flow rates of all injectors is input into one well. Since the wells are usually located relatively close together this assumption should provide a realistic approximation of the area of review. The program is designed to calculate the formation pressure

utilizing an input flow rate or by determining a maximum allowable flow rate utilizing an input formation fracture pressure.

The static mud column pressure calculated by INJWEL depends on the mud density.

$$P_s = 0.052\rho h \qquad (3\text{-}3)$$

Since the mud density varies with each abandoned well, the static mud column pressure will also vary. To define properly the area of review it is necessary to take the extreme case where P_s is a minimun. Therefore the density to be utilized in the static mud column pressure calculation must be the lowest density recorded in the abandoned wells within a 2½ mile radius of the injectors. Equation 3-3 can be modified to yield the appropriate equation:

$$P_s = 0.052\ \rho_{min}\ h \qquad (3\text{-}8)$$

The gel strength presure calculated by INJWEL is inversely proportional to the diameter of the abandoned well. Since the diameters of the abandoned wells vary, proper definition of the area of review requires the use of the minimun gel strength pressure calculated in the abandoned wells located in the 2½ mile radius of the injectors. This minimun theoretically will occur in the abandoned well drilled with the largest bit size at the injection formation depth. Equation 3-5 can be modified to yield the appropriate equation:

$$P_g = 3.33 \times 10^{-3} \frac{Gsh}{D_{max}} \qquad (3\text{-}9)$$

Where: D may denote the largest bit diameter at the injection formation depth plus two inches.

Step 4

The information obtained in step two is utilized in this step to determine the formation pressure at each of the abandoned wells for the specified time period. The formation pressure is calculated by utilizing a computer program PRES (Appendix (G)) which has undergone some FORTRAN modification from the original program developed by Carter.[13] The program determines the formation pressure at each abandoned well at specified time periods. For use in calculating the area of review the time must equal the life of the injection well or wells. Although an average injection rate would suffice, the program is capable of determining the formation pressure at a specified time for wells injecting at varing rates. The use of PRES is demonstrated in the example contained in Appendix E. In addition to calculating the pressures at the abandoned wells PRES also generates an X-Y Plot which locates the injectors and the abandoned wells on an appropriate grid system. The x-y Plot also contains an isobar which represents the static mud column + gel strength pres-pressure calculated by INJWEL in step three. This isobar defines the area of review. Inside the area encompassed by the

isobar the formation pressure exceeds the static mud column + gel strength presure and the potential for contamination of underground sources of drinking water by migration of injection and/or formation fluid up the abandoned well bore exists. The X-Y Plot graphically defines the area of review and clearly delineates the wells which fall within the area of review and will require further examination.

INJWEL and PRES both provide means of calculating the required pressures and utilize the pressures to graphically display the area of review. INJWEL relates the pressure cone which results from the injection operation and it clearly displays the rapidity with which the pressure falls off with increased distance from the well. The cone demonstrates the sensitivity of the area of review to small pressure changes at large radial distances from the injector. In other words a small variation in the static mud column plus gel strength pressure at large radial distances can result in a big variance in the area of review defined. PRES provides a graphical representation which requires little explanation. The area of review is clearly defined with respect to the injection wells and the abandoned wells.

Step 5

If after completing steps one through four it is found that all wells contained within the static mud column plus gel strength pressure isobar, the area of review, have a mud density greater than the density used to calculate the static mud column pressure in step three then the static mud column pressure should be recalculated using the minimun mud density obtained for all abandoned wells within the area of review defined by steps three and four. Should all abandoned wells within the defined area of review have a bit size at the injection formation less than that used to calculate D_{max} in equation (3-9) then the gel strength should be recalculated utilizing the largest bit diameter encountered in the abandoned wells contained within the isobar defining the area of review in step four. This iterative process can be repeated until the wells contained within the area of review have the same gel strength and static column pressure as determined in the previous iteration. Once the iterative process is completed the area of review defined is the true area of review for the particular injeciton well system in question.

Step 6

Step 5 defines the area of review for the proposed injection operation. Reference 8 requires that correc-

tive action be taken on all wells within the area of review which are inadequately constructed, completed, or abandoned and which as a result of the injection activity may cause the pollution of fresh water. Utilizing the developed theory it is possible to evaluate each abandoned well within the area of review on an individual basis to determine if the injection activity will cause interformational fluid transfer at that particular well. Utilizing equations (3-8) and (3-9) to evaluate each well it is possible to determine those wells which present a pollution problem. Those abandoned wells where $P_f > P_s + P_g$ should be reviewed to determine if corrective action is necessary.

Step 7

Once the wells requiring corrective action are identified the action should be inetiated. The EPA and TDWR standards [7,8] for action required to prevent pollution of ground water sources of drinking water indicate that corrective action shall consider the following factors:

(1) Toxicity and volume of the injected waste;

(2) Toxicity of native fluids and by-products of injection;

(3) Population potential affected;

(4) Geology and hydrology;

(5) Completion and plugging records:

(6) Abandonment procedures in effect at the time a well is abandoned; and

(7) Hydraulic connections with fresh water.

Normally corrective action should involve the location and re-entry of the well and proper plugging in accordance with the Texas Railroad Commission rules and regulations. In some cases this may not be possible due to inability to locate the well site or because construction has covered the site. In these cases two options are: (1) lower the injection volume so that lower pressures will occur or (2) drill a nearby monitor well in the drinking water source.

Summary

The heavy dependance on ground water for daily needs demands that every precaution be taken to protect the remaining supplies. Subsurface disposal of hazardous wastes by injection is an alternative which provides for the protection of subsurface sources of drinking water. Subsurface disposal presents less water pollution potential than the commonly utilized surface disposal methods. Economic conditions must be favorable to subsurface injection before waste generators will consider it as a viable waste disposal option in geologically favorable areas. The cost of compliance with the UIC program regulations

may be the deciding factor when the costs of disposal options are evaluated. The extent of corrective action required within the area of review could represent a significant portion of the costs required to comply with UIC regulations. The disposal option selected and the resulting impact potential on underground sources of fresh water may be controlled by the size of the area of review. Therefore, it is necessary to have a procedure which will ensure the protection of ground water while eliminating unnecessary expendatures for corrective action.

Conclusions

The following conclusions were drawn from the results of this investigation.

1.) The costs associated with record searches and field surveys undertaken to determine the plugging history of abandoned wells can be avoided if the wells lie outside the area of review determined by the proposed procedure.

2.) The costs associated with plugging abandoned wells located outside the calculated area of review can also be avoided.

3.) The procedure minimizes the cost of locating and plugging abandoned wells since it allows the user to reduce the number of abandoned wells located within the area of review by varing the well locations, the selection of injection formation and flow rates.

4.) Utilization of the procedure to determine the area of review should present no risk to subsurface sources of drinking water since the procedure considers all abandoned wells within the 2½ mile radius of the injection wells and utilizes the data obtained to design for the worst possible conditions.

5.) The area of review determined will decrease as the depth to the injection formation increases. Thus where equivalent injection formations exist injection into the deeper formation will result in the smaller area of review determination.

6.) The 20 lb/100SF gel strength utilized for the determination of the gel strength pressure represents the minimun ultimate gel strength expected to be encountered when evaluating abandoned wells drilled with water-base drilling fluids.

7.) The procedure described can not be applied to zones of lost circulation or to abandoned wells drilled with muds that do not exhibit the thixotrophic property of gel strength.

8.) Since the pressure cone resulting from the injection operation falls off quickly the size of the area of review varies greatly with small pressure changes at large radial distances from the injectors.

Recommendations

The following recommendations are offered in an effort to better define the area of review for hazardous waste disposal wells:

1.) That the procedure outlined in the previous sections be utilized to determine the area of review for hazardous waste disposal wells.

2.) That research be undertaken to determinme the long term effects of bore hole conditions on the gel strength of water-base drilling fluids.

3.) That research be undertaken to determine the degree of component segregation which water-base muds undergo while remaining quiescent in the bore hole for long periods of time.

4.) That other procedures utilized to determine the area of review consider the characteristics of the drilling fluid which occupies the abandoned well bore.

APPENDIX A

STANDARDS AND TECHNICAL CRITERIA APPLICABLE TO INDUSTRIAL WASTE INJECTION

STANDARDS AND TECHNICAL CRITERIA APPLICABLE TO INDUSTRIAL WASTE INJECTION

The regulations promulgatged by the 24 June 1981 Federal Register were proposed under the authority of the Safe Drinking Water Act and are designed to protect the quality of underground sources of drinking water from contamination which could result from the injection of waste fluids into subsurface formations. The regulations established the technical criteria and standards for use by states and the EPA in the developement and implementation of state UIC programs. The regulations promulgated by the 24 June 1980 Federal Register do not etablish requirements for owners or operators of injection wells. They establish requirements for state and EPA officials to be used in developing the state UIC programs which, when they become effective, will in turn establish enforceable requiremnts for owners or operators of injection wells.

The Texas injection well act incorperates the standards and technical criteria promulgated by the 24 June 1981 Federal Register into the Texas UIC program. Since a large percentage of the waste injection wells in operation in the United States are located in the State of Texas, the provisions of Injection Well Act will be reviewed to provide

an overview of the standards and technical criteria which apply to the owners and operators of industrial waste disposal wells within Texas. UIC programs will vary from state to state but compliance with the Federal Register ensures that all programs must incorporate the same basic standards and technical criteria.

The Injection Well Act requires owners and operators of industrial waste disposal wells to comply with the following:

A Permit Application - It is the responsibility of the owner of a waste injection facility to submit an application for permit; except if the facility is owned by one individual and operated by another, then it is the responsibility of the operator to submit the application for permit. Each application for permit shall include the following:

1.) Name, mailing address, and location of the injection operation for which the application is submitted;
2.) Ownership status as federal, state, local, private, public or other;
3.) Operator's name, mailing address, and telephone number;
4.) A brief description of the type of business operated;

5.) Activities conducted at the site which require a permit;

6.) Statement of up to four SIC codes which best describe the principal products or services provided by the facility;

7.) An appropriate map which shows the facility and each of its intake and discharge structures. The map shall depict the approximate boundaries of the tract of land to be used by the applicant and shall extend at least one mile beyond the tract boundaries sufficient to show the following:

   a.) Each well, spring, and surface water body within the map area;

   b.) The presence of public roads, towns and the nature of developement such as residential, commercial, agricultural, recreational, undeveloped or otherwise within the map area;

   c.) The location of other waste disposal activities conducted at the tract but not included in the permit application;

   d.) The ownership of tracts of land within a reasonable distance from the proposed injection point; and

- e.) Such other information as reasonably requested.

8.) A list of all permits or construction approvals received or applied for under the provisions of other environmental protection regulations or programs.

9.) Whether the facility is located on Indian lands;

10.) A supplementary technical report. The report shall be prepared by a registered professional engineer or other qualified person and shall be submitted when requested. The report shall include the following:

- a.) A general discription of the facility and systems used in connection with the waste injection activity.
- b.) For each injection well:
  - i.) The injection rate of the disposal waste stream, including appropriate averages, the maximun rate of injection over representative periods of time, and detailed information regarding patterns of injection; and
  - ii.) The physical and chemical properties of the defined waste injection stream; chemical, physical, thermal, organic, bac-

teriological, or radioactive, as applicable.

c.) Such other information as may be reasonably required for an adequate understanding of the project or operation.

11.) Additional information as follows:

a.) A plugging and abandonment plan;

b.) A letter from the Railroad Commission of Texas stating that the drilling of a disposal well and the injection of the waste into the selected subsurface disposal formation will not endanger or injure any oil or gas formations.

H. Terms and Conditions of the Permit - Acceptance of the permit by the person to whom it is issued constitutes an acknowledgement and agreement that he will comply with all the terms and conditions contained within the permit, the rules of the TDWR and any other orders issued by the TDWR. Conditions applicable to all permits issued under the UIC program are as follows:

1.) All reasonable steps required to minimize or correct any adverse impact on the environment resulting from noncompliance with the permit must be promptly undertaken;

2.) All facilities shall be properly operated and maintained at all times;

3.) The permittee shall provide to the TDWR, upon request, copies of records required to be kept by the permit;

4.) The permittee shall notify the TDWR prior to any physical modifications which would require a permit modification;

5.) The permittee shall not begin any mofications which would result in noncompliance with other permit requirements without written approval from the TDWR;

6.) Within 24 hours after occurance, the permittee shall orally notify the TDWR of any noncompliance which may endanger health or the environment.

7.) The permitted shall allow entry to and inspection by TDWR personnel as prescribed by Texas law;

8.) The permittee shall monitor and obtain samples and measurements required to provide sufficient evidence that the disposal operation is conducted in compliance with the permit provisions.

9.) Monitoring results shall be provided to the TDWR at the intervals specified in the permit; and

10.) The permittee shall promptly submit facts or information to the TDWR if it is noted that such facts were omitted from the permit application, or were submitted incorrectly.

C. Conditions Applicable to Individual Permits - The following conditions will be determined on a case-by-case basis.

1.) The duration of the permit varies with the type of waste disposal operation. Industrial waste disposal (Class 1) wells shall be permitted for a fixed term not to exceed 10 years;

2.) The type, intervals and frequency of monitoring, recording and reporting shall be determined to yield representative data of the disposal operation;

3.) A schedule of compliance prescribing a timetable for achieving compliance with the permit conditions an appropriate regulations may be incorperated into the permit.

D. Corrective Action - For wells within the area of review which are inadequately constructed, completed, or abandoned, and which as a result of the injection operation may cause the pollution of fresh water, the TDWR will

incorperate into the permit conditions requiring corrective action adequate to prevent such pollution. Permits issued for existing injection wells requiring corrective action may include a compliance schedule prescribing the time within which the corrective action must be completed.

D. Financial Responsibility - The permittee shall obtain a performance bond or other equivalent form of financial assurance or guarantee approved by the TDWR to ensure that closing, plugging and abandoning of the injection operation is accomplished in the manner prescribed by TDWR.

E. Surface Facilities - The surface facilities associated with a hazardous waste disposal well must comply with the rules and regulations which are applicable to hazardous waste management facilities.

F. Record Retention- The permittee shall maintain all records concerning the nature and composition of the injected waste until five years after completion of the plugging and abandonment of the well.

G. Site Identification and Access - Industrial waste disposal wells shall have the following:

1.) A posted sign at the well site which shall show the name of the company, company well number and permit number.

2.) An all-weather road maintained to allow access to the injection well and related facilities.

3.) Painting and maintainance of the wellhead and associated equipment to ensure proper working order without significant leaks.

H. Standards and Conditions Which Apply to Class I or Industrial Waste Disposal Wells

   1.) An injection well must demonstrate mechanical integrity. An injectin well is said to have mechanical integrity if there is no significant leak in the casing, tubing, or packer, and if there is no significant fluid movement through vertical fluid channels adjacent to the injection wellbore. The following tests shall be conducted to evaluate the mechanical integrity of an injection well:

      a.) Monitoring of annulus pressure, or a pressure test with liquid or gas to detect any leaks in casing, tubing, or packer; and,

    - b.) A temperature or noise log to detect any fluid movement through vertical channels behind the casing.

2.) Corrective action required to prevent or correct pollution of underground sources of drinking water shall consider the following factors:
    - a.) toxicity and volume of the injected waste;
    - b.) toxicity of native fluids and by-products of injection;
    - c.) population potential affected;
    - d.) geology and hydrology;
    - e.) history of the injection operation;
    - f.) completion and plugging records;
    - g.) abandoment procedures in effect at the time a well was abandoned; and,
    - h.) hydraulic connections with fresh water.

3.) The TDWR will certify construction and completion of an injection well or project which is constructed and completed in compliance with the requirements of a permit. To determine if such certification will be made, TDWR shall consider the following:
    - a.) logging and testing program data on the well;
    - b.) a demonstration of mechanical integrity;
    - c.) anticipated operating data;

d.) the results of the formation testing program;

e.) the injection procedure;

f.) the compatibility of injected waste with formation fluid in the injection zone and with the minerals in both the injection and confining zones; and,

g.) the status of corrective action required for abandoned wells in the area of review.

4.) Prior to abandoning hazardous waste disposal wells the well shall be plugged with cement in a manner which will not allow the upward migration of fluids out of the injection zone either into or between freshwater aquifers. At least 90 days notice will be given the TDWR before the plugging and abandonment commences in compliance with an approved plan. Placement of the cement plug shall be accomplished utilizing one of the following aproved methods:

a.) the Balance Method;

b.) the Dump Bailer Method; or

c.) the Two-Plug Method.

The adequacy of a plugging and abandonment plan shall be determined by considering the following:

a.) the type and number of plugs to be used;

b.) the placement of the plugs;

c.) the type, grade and quantity of the plugging material used;

d.) the method of placement of the plugs;

e.) the procedure used to plug and abandon the well;

f.) any new information obtained on wells within the area of review;

g.) geologic or economic conditions; and,

h.) such other factors that may affect the adequacy of the plan.

Within 30 days after completion of plugging, the permittee shall file a plugging report with the TDWR.

5.) All hazardous waste disposal wells shall be cased and cemented to prevent the movement of fluids into or between fresh water aquifers. Sufficient cement shall be used to fill the annulus between the casing and the wellbore to ground level. The casing and cement used shall be selected to ensure that the final design is adequate for the life of the well. The minimun depth of the surface casing will be determined by the TDWR and will be selected to protect fresh water formations. The following factors

shall be considered when specifying casing and cementing requirements:

a.) depth to the injection zone;
b.) injection pressure, formation pressure, wellbore pressure, and axial loading;
c.) hole size;
d.) size and grade of all casing;
e.) corrosive effects of injected waste, formation fluids, and temperatures;
f.) lithology of injection and confining intervals;
g.) types and grades of cement.

6.) All hazardous waste disposal wells shall inject through tubing with either a packer set above the injection zone or a fluid seal system approved by the TDWR. Tubing, packers or fluid seals shall be selected utilizing the following considerations;

a.) setting depth; characteristics of the injected waste;
c.) injection pressure;
d.) annular pressure;
e.) rate, temperature, and volume of injected waste; and,
f.) size of casing.

7.) Appropriate logs and other tests shall be completed during the drilling and construction stages of the hazardous waste injection well. A minimun of the following logs and tests shall be conducted:

- a.) deviation checks;
- b.) Spontaneous Potential (SP), resistivity or Gamma-Resistivity, and caliper logs before the surface casing is installed;
- c.) SP, resistivity or gamma-resistivity, and caliper logs before intermediate and long string casings are set and a cement bond log, a gamma-ray log and an inclination survey after casing is set;
  - d.) pressure testing of all casings;
  - e.) full-hole cores of the injection zone and lowermost overlying confining zone;

8.) After completion of the well, injectivity tests shall be performed to determine the well capacity and reservoir characteristics.

9.) The following operating requirements are imposed:

- a.) Injection pressure at the wellhead shall be limited so as to assure that the pressure in the injection formation during injection will not initiate new

fractures or propagate existing fractures in the injection formation;

b.) Injection outside the outermost casing is prohibited.

c.) The annulus between the tubing and the casing shall be filled with a fluid approved by the TDWR.

d.) Monthly average and instantaneous rates of injection, and annual and monthly volumes of injected waste shall not exceed limits specified by the TDWR.

e.) The chemical and physical characteristics of the injected waste shall be maintained within specified permit limts.

f.) The TDWR shall be notified if any workover operation or corrective maintenance which involves taking the injectino well out of service is contemplated.

10.) Monitoring requirements include the following:

a.) Sampling and analysis of injected waste with sufficient frequency to yield representative data of the characteristics;

   b.) Gauges so that the tubing and casing annulus pressures can be monitored at all times;

   c.) The installation of continuous recording devices to record injection tubing pressures, injection flow rates, injection volumes, tubing-long string casing annulus pressure, and any other specified data.

   d.) The demonstration of mechanical integrity at least every five years during the life of the well.

   e.) The monitoring of wells within the area of review to observe water quality and determine if waste migration has resulted.

11.) Reporting requirements are as follows:

   a.) Prior to operating the injection well the permittee shall within 90 days after completion of the well submit to the TDWR the following:

      i.) A completion report providing the drilling and completion history, casing and cementing records, well logs, injectivity tests performed on the well and a sur-

veyors plat showing the exact location and giving the latitude and longitude of the well.

ii.) A well data report on forms supplied by the TDWR.

b.) The permittee shall provide the health and pollution control authorities of the county, city and town where the well is located with a copy of the permit prior to start-up.

c.) The permittee shall notify the TDWR in writing of the anticipated well start-up date.

d.) Within 20 days after the last day of each quarter the permittee shall file a quarterly Report of Injection Operation.

e.) An Injection Zone Annual Report shall be filled with the December quarterly Report of Injection operation. The report shall provide an updated report of the pressure effects of the injection well on the injection formation.

f.) The permittee shall within 45 days after completion of a test for mecha-

nical integrity provide the data and an interpretation of the results to the TDWR.

g.) The permittee shall notify the Austin office of the TDWR within 24 hours of any change in monitoring parameters which could reasonably be attributed to a leak or other failure of the well equipment or injection formation integrity.

h.) Within 60 days after the completion of a workover, a report shall be filed with the TDWR. During major workovers the bottom pressure shall be determined.

12.) Record keeping requirements are as follows:

- a.) All monitoring required by the permit, including continuous records of:
    - i.) surface injection pressure,
    - ii.) tubing-long string annulus pressure,
    - iii.) injection flow rate.
- b.) Monthly total volume of injected wastes.

c.) Periodic well tests of the following:

  i.) Injection fluid analyses,

  ii.) Bottom hole pressure determinations, and

  iii.) Mechanical integrity

d.) All records shall be made available upon request of a representative of the TDWR.

e.) The permittee shall retain for a period of three years from the date of record, records of all informaiton resulting from any monitoring activities or other records required by the permit.

APPENDIX B

THE IMPORTANCE OF DRILLING FLUID TO THE ROTARY DRILLING METHOD

THE IMPORTANCE OF DRILLING FLUID TO THE ROTARY DRILLING METHOD

The Rotary Drilling Method

The rotary drilling method employs a rotating drill string, a series of casings ans collars, to apply a force to a connected drill bit which interacts with the rock being drilled. The force applied to and the rotating action of the bit causes the rock to fail. A drilling fluid is continuously circulated down the inside of the drill string, out the nozzels of the bit, and up the annular space between the well-bore and the drill pipe to facilitate the removal of the cuttings generated by the bit. As the drilling continues additional joints of drill pipe are added. When the bit becomes dull the drilling mud circulation is discontinued, the drill string is removed from the hole, the bit is replaced, the drill string is run back into the hole and mud circulation is restarted. Once the mud is circulated to the surface it is diverted through a series of tanks and pits designed to allow the mud to release the cuttings it has removed from beneath the bit. The pits also provide the operator an opportunity to condition the mud so that it is capable of per-

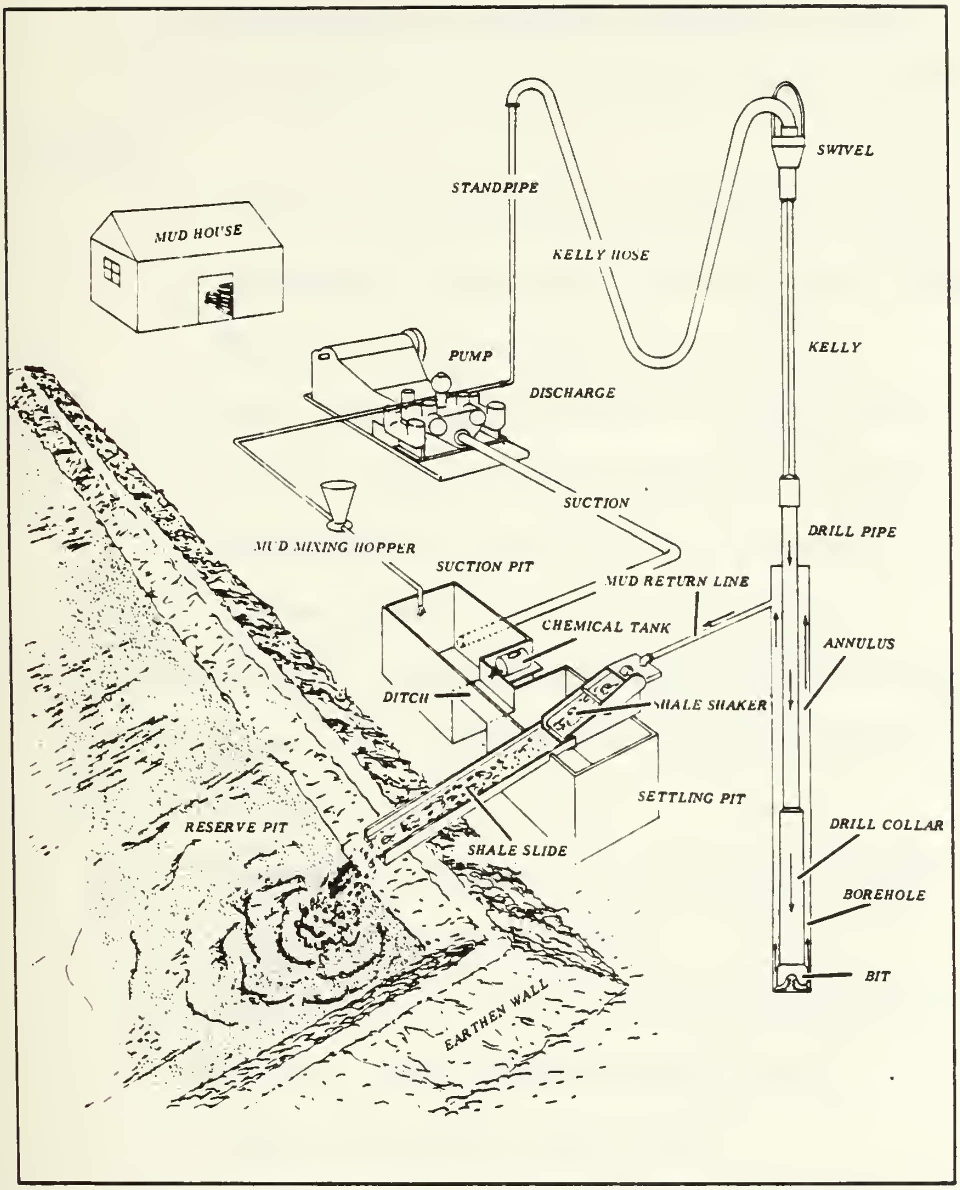

FIGURE 8. Typical Drilling Mud Circulating System (From[23])

forming the desired functions. Figure (8) shows a typical mud circulating system.

The Functions of Rotary Drilling Fluids

Rotary drilling fluids perform the following functions:

1.) Remove cuttings from beneath the bit, transport them up the annulus, and deposit them at the surface.
2.) Cool and clean the drill string and bit.
3.) Control encountered formation pressures by preventing the inflow of formation fluids into the wellbore.
4.) Form an impermeable filter cake to seal the pores and voids in formations penetrated by the bit.
5.) Suspend cuttings during periods when circulation is suspended.
6.) Aid in the collection of information from cuttings, cores, and wireline logs.
7.) Improve the drilling rate.
8.) Release entrained gas at the surface.
9.) Trasnmit hydraulic horsepower to the drilling bit.
10.) Minimize wellbore erosion.

11.) Lower swab and surge pressures and pressures required to inetiate circulation.

Composition and Types of Drilling Fluids

A wide and varied range of fluids are utilized in the rotary drilling method. The fluids range from air and natural gas to fluids two to three times as dense as water. Table 3 lists the classifications of drilling fluids and briefly outlines their principal components and characteristics. The commonly used drilling muds consist of:[14]

1.) A continuous liguid phase (usually water).
2.) A dispersed gel-forming phase such as colloidal solids (usually bentonite clay) and/or emulsified liquids (usually oil) which furnish the desired viscosity, thixotrophy, and filter cake.
3.) Other dispersed solids such as weighting material (usually barite), sand and cuttings.
4.) Various chemicals to control mud properties within desired limits.

The choice of drilling mud for a particular well is dependant upon the geologic conditions which exist at the formation being drilled and is guided by the mud functions which are most critical to the well in question. Other

TABLE 3

CLASSIFICATION OF DRILLING FLUIDS

Classification	Principal Ingredients	Characteristics
GAS:		
Dry Air	Dry Air	Fast frilling in dry, hard rock No water Influs Dust
Mist	Air, water or mud	Wet formations but little water injlux High Annular velocity
Foam	Air, water, foaming agent	Stable rock Moderate water flow tolerated
Stable foam	Air, water containing polymers and/or bentonite;foaming agent	All"reduced-pressure" conditions: Large volumes of water, big cuttings removed at low annular velocity Select polymer and foaming agent to afford hole stability and tolerate salts Foam can be formed at surface
WATER:		
Fresh	Fresh Water	Fast drilling in stable formations. Need large settling area, flocculants, or ample water supply and easy disposal
Salt	Sea Water	Brines for density increase and lower freezing point Limited to low perm rocks
Low Solids Muds*	Fresh water,polymer, bentonite	Fast drilling in component rocks Mechanical solids removal equipment needed Contaminated by cement, soluble salts

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NOTES:

Detergents, lubricants, and/or corrosion inhibitors may be added to any water composition

* When barite is added to raise the density of these muds, they are called "nondispersed" muds.

TABLE 3 CONT

CLASSIFICATION OF DRILLING FLUIDS

Classification	Principal Ingredients	Characteristics
Spud Mud	Bentonite and water	Inexpensive
Salt Water Muds*	Sea water, brine saturated salt water, salt-water clays, starch, cellulosic polymers	Drill rock salt Work overs Drilling salts other than halite may require special treatment
Lime Muds*	Fresh or brackish water, bentonite (or native clays), lime, chrome-lignosulfonate Lignite, sodium chromate and surfactant for high temperatures	Shale drilling Simple maintenance at medium densities Max. temp. 300°F with lignite added
Gyp Muds**	Same as lime muds, except substitute gypsum for lime in above composition	Shale drilling Simple maintenance Max. temp. 325°F Unaffected by anhydrite, cement, moderate amount of salt pH 9-10
CL-CLS Muds**	Fresh or Brackish water, bentonite caustic soda, chrome lignite, chrome-lignosulfonate Surfactant added for high temperature	Shale drilling Simple maintenance Max Temp. 350°F Same tolerance for contaminants as gyp muds pH 9-10

NOTES:

*Diesel oil is often added to these muds, frequently along with an emulsifying agent.

**Temperature stability of these muds is increased by removing calcium and adding lignite and surfactant (DMS)

TABLE 3 CONT

CLASSIFICATION OF DRILLING FLUIDS

Classification	Principal Ingredients	Characteristics
Potassium Muds	Potassium chloride acrylic, bio or cellulosic polymer, some bentonite	Hole stability Mechanical solids-removal equipment necessary Fast drilling at minimum solids content pH 7-8
OIL:		
Oil	Weathered crude oil Asphaltic crude + soap + water	Low-pressure well completion and workover Drill shallow, low-pressure productive zones Water can be used to increase density and cutting-carring ability
Asphaltic Muds	Diesel oil, asphalt, emulsifiers, water 2-10%	The composition of oil muds can be designed to satisify any density and hole stabilization requirements and temperature requirements to 600°F
Non-Asphaltic Muds("Invert")	Diesel oil, emulsifiers, oleophilic clay, modified resins and soaps, 5-40% water	High initial cost and environmental restrictions, but low maintenance cost

NOTES:

(1) Density of oil muds can be raised by addition of calcium carbonate or barite.

(2) Calcium chloride is added to the emulsion water phase to increase shale stability.

(From Gray, Darley & Rogers[18])

significant factors include economics and the availability of make-up water.

Important Static Drilling Fluid Properties

Two of the properties of drilling fluid which enable it to perform its required functions are also important when determining the pressures which act on a static mud column in an abandoned well. These properties must be understood in order to evaluate the pressures which could cause formation fluids to migrate up an abandoned wellbore. The pertinent properties are the gel strength and the mud density. A review of the functions these mud properties perform provides background information which may be helpful when attempting to evaluate the pressures which act at the static wellbore.

The Importance of Controlling the Gel Strength in Drilling Fluids

Proper control of the gel strength of a drilling fluid is essential to the adequate functioning of the mud. The gel strength must be high enough to suspend cuttings during periods of non-circulation, but low enough to:[15]

1.) Allow sand and shale cuttings to settle out and entrained gas to escape in the mud pits.
2.) Permit ready breaking of circulation as the pump is started.

3.) Minimize swabbing effects when pulling the drill string from the hole.

The most common causes of high gel strength during drilling are:

1.) Insufficient deflocculation of the clay colloids which may require the addition of chemical thinners.

2.) To high a concentration of solids; the accumulated solids must be reduced by dilution or mechanical seperation.

3. Contamination from drilling anhydrite, gypsum, cement, rock salt or from a salt-water flow: The effects of the contaminants can be nullified by using thinners and filtration control agents.

Blow outs may result if the gel strength is too high. High gel strengths require excessive pump pressures to initiate mud circulation thus the increased pressure may be sufficient to fracture a weak formation and cause lost circulation. High gel strength may cause a suction when pulling the drill pipe out of the hole, this situation may swab formation fluid into the hole producing a kick which could lead to a blowout.

The Removal of the Bit Cuttings

The removal of cuttings from beneath the bit and the transport of the cuttings to the surface is the pri-

mary function which all rotary drilling fluids must perform effectively if the bit penetration is to progress optimally. The bit nozzel and annulus velocities of the drilling mud circulated during drilling operations are the chief factors which control cutting removal and transport, respectively. Annulus velocities between 100 and 200 ft/min are frequently used. The annular mud velocity is dependant on pump capacity, pump speed, bore hole size and drill pipe size. The viscisity of the mud determines the efficiency of the cuttings removal for a specific velocity. While changing bits and during other periods of inactivity, the drilling fluid must be capable of suspending the cuttings being circulated to the surface. If the cuttings are not suspended during non-circulation they will fall back towards the bottom of the hole where they could cause the bit or drill collars to stick and produce an expensive fishing job.

Mud Properties Which Enable the Static Mud Column to Suspend Cuttings

The primary mud property which acts to suspend cuttings in the static mud column is the gel strength. Gel strength is the result of a gelled structure which developes in common drilling fluids when they remain in a quiescent state. The gel structure acts to support the weight of the suspended cuttings. Since the bouyance

force exerted by a static fluid increases with its density, an increas in mud density will result in a greater ability of the mud to support cutting during periods of non-circulation.

Controlling Formation Pressures

The mud density also accomplishes another important function, that of controlling encountered formation pressures by preventing the inflow of fluids into the wellbore. It is imperative that the mud density be fully controlled since serious drilling hazards may result if it isn't. A fluid kick may result if the formation pressure exceeds the static mud column pressure. The kick occurs when the formatin fluid (gas, oil or water) enters the bore hole. As the fluid rises up the annulus, it expands and displaces the drilling mud contained in the annulus. The loss of mud in the annulus further reduces the static mud column pressure, allowing more fluid to enter the wellbore. If the situation is not brought under control a blowout could result. When the density of the mud is excessive, the pressure of the static mud column may be sufficient to fracture weak formations which could result in lost circulation. Lost circulation is defined as a significant loss of drilling mud to a formation. When this occurs the mud column will drop and a reduction in the static mud column pressure results.

If the static mud column pressure drops below the formation pressure the risk of a blowout will again be encountered. The normal pressure gradient, the gradient utilized to determine the formation pressure in normally pressured zones, is considered to be the pressure exerted by a column of typical formation water and is equal to 0.465 psi/ft of depth in the Texas Gulf Coast Area.

APPENDIX C

THEORY OF PRESSURE BUILDUP IN INJECTION ZONES

THEORY OF PRESSURE BUILDUP IN INJECTION ZONES

The Diffusivity Equation

Mathews and Russell[12] developed the basic differential equation for the unsteady state radial flow of a slightly compressible fluid from an injection well. The diffusivity equation provides the fundamental means of investigating the fluid flow which occurs in porous media. The equation is derived by applying the idea of continuity to a general mass balance:

$$\frac{\partial}{\partial X}\left(\frac{\rho K_x}{u}\frac{\partial \Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho K_y}{u}\frac{\partial \Phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\rho K_z}{u}\frac{\partial \Phi}{\partial z}\right)=\frac{\partial}{\partial t}(\phi\rho) \qquad \text{(C-1)}$$

The following assumptions are applied to reduce the diffusivity equation to a usable form:

1.) single fluid of samll and constant compressibility
2.) homogeneous, isotropic, and constant thickness porous media
3.) negligible gravity effects
4.) constant fluid viscosity and media porosity
5.) horizontal flow
6.) radial flow

Utilizing the assumptions, equation (C-1) is simplified to the following differential form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right) = \frac{\phi uc}{k}\frac{\partial P}{\partial t}$$

Constant Injection Into a Reservoir of Infinite Areal Extent

The following boundary conditions are applied to solve the differential equation:

Initial conditions: $\lim_{r \to \infty} P(r,t) = P_i$

$$\lim_{r \to 0}\left(r\frac{\partial P}{\partial r}\right) = \frac{-qu}{2\pi kh}$$

The initial conditions establish the initial pressure throughout the reservoir, and ensures that the system maintains an unsteady state flow. The second condition requires that the flow must approach steady state radial flow when the fluid is at the infinitely small wellbore.

Define a variable,   as:

$$\eta = \frac{\phi ucr^2}{4kt}$$

$$\frac{\partial \eta}{\partial r} = \frac{\phi ucr}{2kt}$$

$$\frac{\partial \eta}{\partial t} = \frac{\phi ucr^2}{4kt^2}$$

By the chain rule:

$$\frac{1}{r}\frac{\partial}{\partial \eta}\frac{\partial \eta}{\partial r} \quad \frac{r\partial P}{\partial \eta}\frac{\partial \eta}{\partial r} = \frac{\phi uc}{k}\frac{\partial P}{\partial \eta}\frac{\partial \eta}{\partial t} \qquad \text{(C-3)}$$

By substitution:

$$\frac{1}{r}\frac{\partial \eta}{\partial \eta}\frac{\phi ucr}{2kt} \quad r\frac{\partial P}{\partial \eta}\frac{\phi ucr}{2kt} = \frac{\phi uc}{k}\frac{\partial P}{\partial \eta} \; -\frac{\phi ucr^2}{4kt^2} \qquad \text{(C-4)}$$

Simplifying:

$$\frac{\phi\, uc}{kt}\,\frac{\partial}{\partial \eta}\left(\frac{\partial P}{\partial \eta}\,\frac{\phi ucr^2}{4kt}\right) = \frac{\phi uc}{kt}\,\frac{\partial P}{\partial \eta}\left(-\frac{\phi ucr^2}{4kt}\right) \qquad \text{(C-5)}$$

Setting things in terms of η :

$$\frac{\partial}{\partial \eta}\left(\eta\frac{\partial P}{\partial \eta}\right) = -\eta\frac{\partial P}{\partial \eta} \quad \text{or}$$

$$\frac{d^2P}{d\eta^2} + \frac{dP}{d\eta} = -\eta\frac{dP}{d\eta} \qquad \text{(C-6)}$$

let $P' = \frac{dP}{d\eta}$

$$P-P_i = \frac{-qu}{4\pi kh}\,E_i(-\eta) \qquad \text{(C-12)}$$

Converting back to polar coordinates:

$$P(r,t) = P_i - \frac{qu}{4\pi kh}\,E_i\left(\frac{-\phi ucr^2}{4kt}\right) \qquad \text{(C-13)}$$

The formation volume factor can be incorporated to express the bottom hole flow rate q or BQ where Q is surface volume flow rate and the equation for constant rate injection by a single well can be presented for use in this report as:

$$P(r,t) = P_i - \frac{QuB}{4\pi kt}\,E_i\left(\frac{-\phi ucr^2}{4kt}\right) \qquad \text{(C-14)}$$

Superposition

The method of superposition allows the modification of equation (C-14) to allow the incorporation of variable flow rates and multiple wells. The modification for variable rate provides the following equation:

$$P(x, y, t) = P_i - \frac{B\ u}{4\pi\ kt} \sum_{j=1}^{m} \sum_{i=1}^{nj} \Delta\ Q_{ij}\ E_i \left(\frac{-\phi\ ucr^2{}_j}{4k(t-t_{ij})} \right) \quad (C-15)$$

where: Q_{ij} = is rate in well j at time t_{ij}

$rj = \sqrt{(x-xj)^2 + (y - yj)^2}$

xj, yj = coordinates of well j

x, y = coordinates where P is evaluated $P(x, y, t)$

For $t > t_{nj}$

NOMENCLATURE

B = Reservoir fluid formation volume factor, reservoir volume/surface volume

c = Fluid compressibility, 1/atmospheres

h = Formation thickness, ft

k = Permeability, darcys

P = Formation pressure, atmospheres

P_i = Initial formation pressure, atmospheres

q = Flow rate, cm^3/sec

Q = Flow rate, cm^3/sec

rij = Radial distance from the injection well, cm

t = Time, sec

t_i = Starting time of 1th well, sec

u = Viscosity, cp

ϕ = Porosity, fraction

APPENDIX D

DETERMINATION OF GEL STRENGTH

DETERMINATION OF GEL STRENGTH

Introduction

When common use, water base drilling fluids remain in a quiescent state a gel structure develops. The strength of this structure is important since the difference between the formation pressure and the static mud column pressure would have to be sufficiently large to break the gel structure before the drilling mud can flow freely in an abandoned well bore. To calculate the formation pressure increase which is required to break the gel strength structure a means of determining the value of the gel strength of the drilling mud is required.

Since the gel strength varies with the mud type and the conditions that act on the mud it is difficult to determine the exact gel strength of the mud in a particular abandoned well bore. To overcome this difficulty it is necessary to review the gel strength characteristics of various mud types and evaluate the factors which act to alter the gel strength structure. The aim of this review is to provide sufficient information to determine the minimum gel strength structure that could be anticipated for any combination of formation, well bore and mud type. The determined minimum gel strength value will be utilized to determine the gel strength pressure for adan-

doned wells in a given waste injection scheme. The calculated gel strength will allow the determination of the formation pressure increase which can result from the waste injection without rupturing the gel strength structure. The following discussion is devoted to the determination of a minimum gel strength value.

Thixotropy

Thixotropy is defined as the property exhibited by certain gels of liquifying when stirred or shaken and returning to the hardened state upon standing.[16] To understand the thixotrophic properties of drilling muds some knowledge of clay minerology is necessary. Nearly all aqueous drilling fluids and some oil-based drilling fluids utilize clay as their colloidal base. Due to their size definition all clay particles fall into the colloidal particle range. Colloidal systems utilized in drilling fluids include solids dispersed in liquids and liquid droplets dispersed in other liquids. These colloidal systems define clay suspension and emulsion muds, respectively. The highly active colloidal paticles comprise a small percentage of the total solids in drilling muds but act to form the dispersed gel forming phase of the mud which furnishes the desired viscosity, thixotropy, and wall cake. Clay particles and organic colloids comprise the two classes of colloids used in mixing of drilling

fluids. The common organic colloids include starch, carboxycelluloses (CMC) and polyacrylomine derivatives.

The clay colloids utilized in common drilling fluids are characterized by a crystaline structure which influences the ability of the clay to retain water. Clays used in fresh water muds consist of hydrated alumnosilicates comprised of alternate plates of silica and aluminum to form layers of each mineral. The plate-like crystals have two distinct surfaces: a flat face surface and an edge surface. Slight surface polarities induce weak electrostatic forces along the faces and edges of the mineral plates. Garison[17] noted that these electrostatic forces attract planer water to the colloidal particles forcing the clays to swell when wet and shrink when dry. The attraction of planer water to the faces of the plates is greater than the attraction of the sheets for each other therefore the structure tends to swell due to the absorbsion of the planer water from the drilling fluid. The bentonite clays demonstrate a strong ability to attract planer water as a result they experience extreme swelling. When in contact with fresh water, the face to face attraction of water by the mineral layers will continue until the swelling reduces the attraction of the plates to the point where they seperate. This seperation results in a higher number of particles and is referred to as disper-

sion. The dispersion causes the colloidal suspension to thicken. The degree of thickening depends on the electrolytic content, salt concentration of the water, time, temperature, pressure, Ph, the exchangeable cations on the clay, and the clay concentration.

Gel Strength, The Measure of Thixotropy

Thixotropy is essentially a surface phenomenon which is characterized by gel strength measurements. The gel strength indicates the attractive forces between particles under static conditions. The strength of the gel structure which forms under static conditions is a function of the amount and type of clays in suspension, time, temperature, pressure, Ph, and the chemical treating agents used in the mud. The factors which promote, the edge-to-edge and face-to-edge assocation of the clay particles, flocculation increase the gelling tendancy of the mud and those factors which prevent the association decrease the gelling tendancy.

Due to their size, colloidal particles remain indefinately in suspension. When suspended in pure water the clay particles will not flocculate. When flocculation occurs the particles form clumps or flocs. These loosely associated flocs contain large volumes of water. If the clay concentration in the mud is sufficiently high, floc-

culation will cause formation of a continuous gel structure instead of individual flocs.

The gel structure commonly observed in aqueous drilling fluids results from salt contamination. Soluable salts are usually present in sufficient quantities to cause at least a mild flocculation. The time required for the gel to attain an ultimate strength depends on the critical concentration of electrolyte required to initiate flocculation, the thinners present, and the concentration of the clay and of the salt present. During drilling the presence of salts and clay particles varies with each formation being drilled, therefore the drilling fluid is monitored and adjustments are made in order to maintain the desired gel strength.

Gel Strength of the Static Mud Column

Gel strength is measured by a multispeed direct indicating viscometer by slowly turning the driving shaft by hand and observing the maximum deflections before the gel structure breaks. The gel strength is normally measured after a quiescent period of 10 seconds (initial gel strength) and 10 minutes. The measurements are taken at surface conditions of standard temperature and pressure. To determine the gel strength of the static mud column in an abandoned well it is necessary to determine the gel strength of the mud under the influence of bore

hole conditions. The initial and 10 minute gel strengths bare no direct relation to the ultimate gel strength of the mud at bore hole conditions. To determine the ultimate gel strength of a mud it is necessary to discuss the factors which act to influence the initial gel strength at bore hole conditions.

Once the drilling operation is completed and the well is abandoned the mud is subjected to conditions vastly different from those encountered at the surface. In the range of formation depths utilized for disposal of industrial wastes the temperature would be expected to range from 80 to 300°F, the pressure from 1500 to 5000 psi and time from days to several years. Several studies have been conducted to determine the impact of time, temperature and pressure on the gel strength of muds at bore hole conditions. The information obtained from this research should provide a means of determining a reasonable minimum gel strength value for the abandoned wells which exist in the range of formations described above.

It is observed that common use water base muds develope high gel strengths after prolonged periods of quiescence. The relationship between gel strength and time varies widely from mud to mud, depending on the composition, degree of flocculation, temperature, Ph, solids, and pressure. Figure (9)[18] indicates the increase in gel

strength with time for various mud types and reveals that there is no well established means of predicting long term gel strengths with time. It is noted in all cases that the gel strength is observed to increase.

Garrison[17] studied the gel strength in relation to time and rate of reaction for california bentonites. He observed that both the speed and the final strength increased with the bentonite percentages. The gelling was found to follow the equation:

$$S = \frac{S'kt}{1+kt} \qquad \text{(D-1)}$$

where S is the gel strength at any time t, S' is the ultimate gel strength, and k is the gel rate constant. Figure (10) indicates that the gel strength forms more rapidly at first then gradually approaches an ultimate value as time elapsed. Equation (D-1) may be rewritten as:

$$\frac{t}{S} = \frac{t}{S'} + \frac{1}{S'k} \qquad \text{(D-2)}$$

which indicates that a plot of t/S verses t should be a straight line. Figure (11) represents the graph of t/S verses t, and indicates the slope of the line is k and the y-intercept is 1/S'k. This approach provides a means to evaluate the ultimate gel strength for each bentonite concentration. Table 4 represents the ultimate gel strengths and rate constants for the five samples shown in figures (10) and (11). Garrison also made measurements on similar

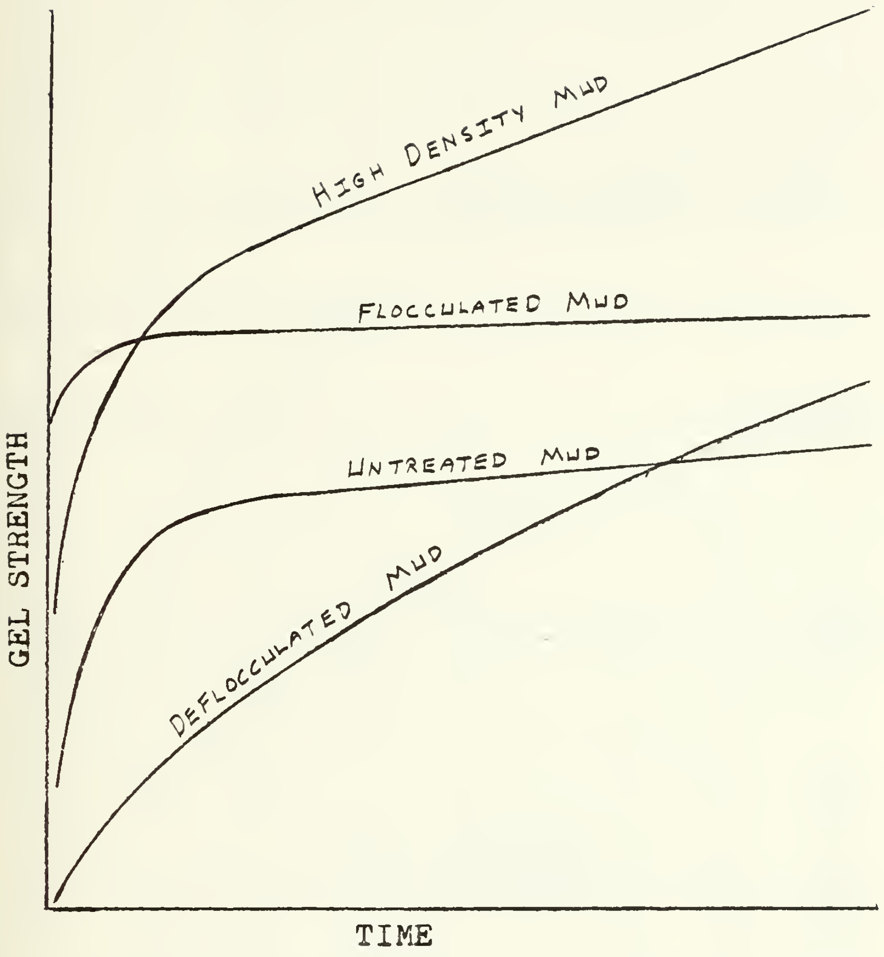

FIGURE 9. Increase in gel strength of various mud types with time (From Gray, Darley, and Rogers[18])

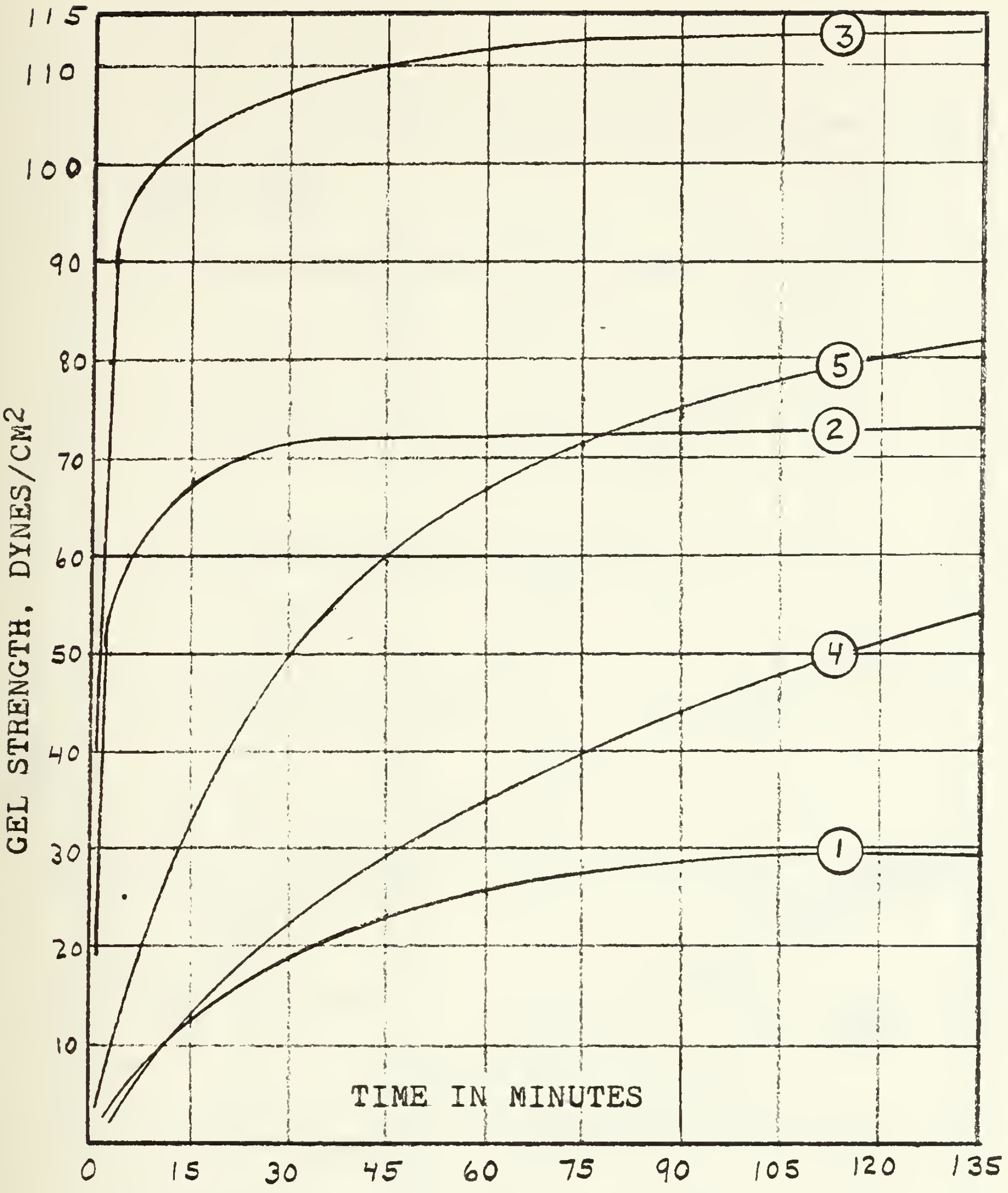

FIGURE 10. Gel Strength in relation to time and rate of reaction (From Garrison[17])

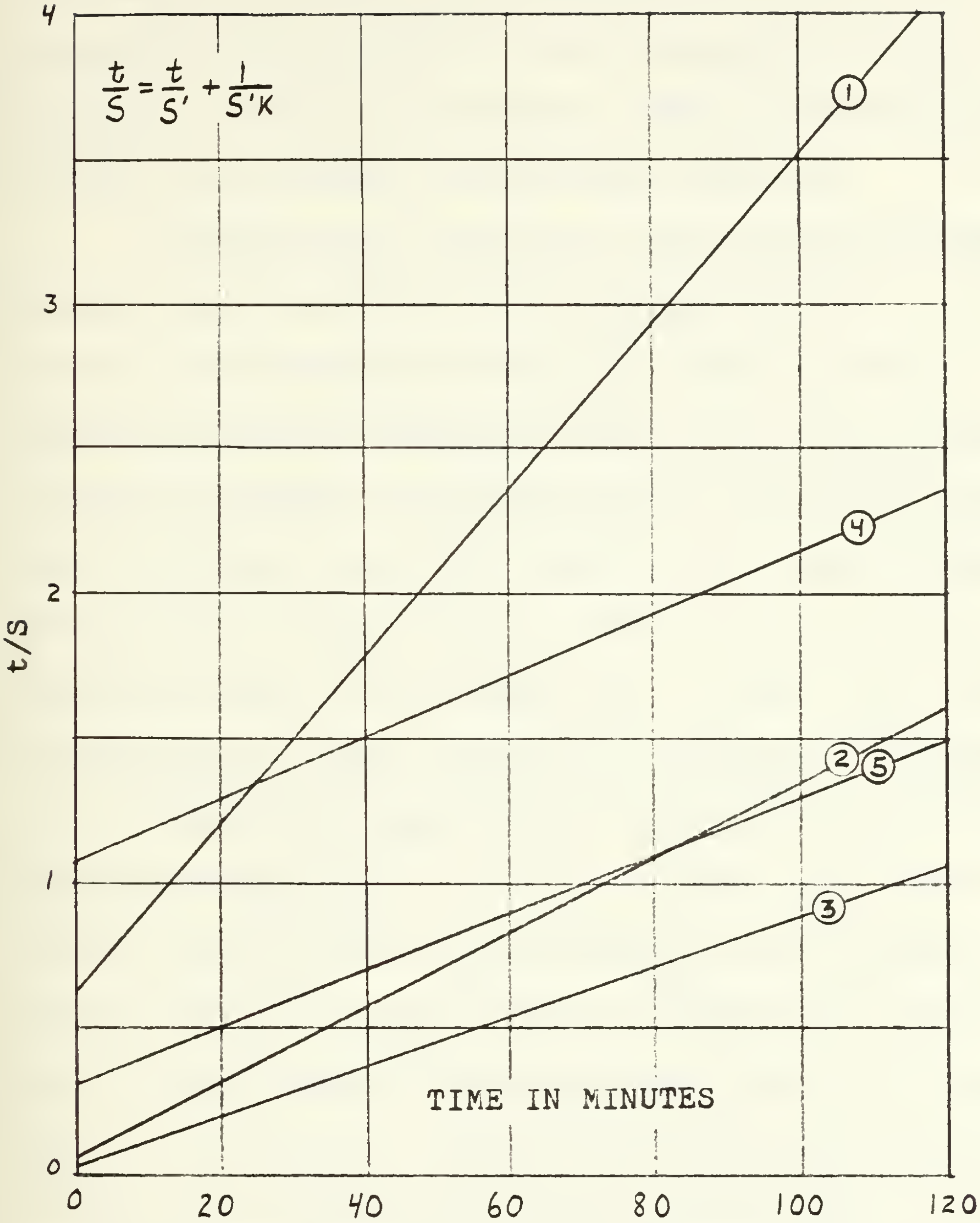

FIGURE 11. Gel Strength and Rate Constants

(From Garrison[17])

suspensions at higher Ph and determined that the ultimate strengths of the bentonite gels increased with each suspension as the Ph increases. Table 5 refects the Ph - ultimate gel strength relationship observed.

Garrison also noted that the treating of muds with thinners had the effect of decreasing the rate of gelling but not the ultimate gel strength. Thus it can be concluded that the reduced initial and 10 minute gel strengths recorded for treated muds reflect the reduced rate of gelling and do not indicate that the ultimate gel strength will be any less than that recorded for an untreated sample of the same mud. In fact, the ultimate gel strength may even increase as indicated in table 4.

Garrison's work does not indicate that all muds comply with equation (D-2), but it does point out that the initial and 10 minute gel strengths do not provide a reliable means of predicting the ultimate gel strength. Weintritt and Hughes[19] conducted progressive gel strength tests on ferrochrome lignosulfonate muds for periods up to 16 hours and obtained the results presented in table 6. They noted that although mud E and mud F had similar properties, Mud F developed only a moderate gel strength while that of Mud E was much greater. Once again it is observed that the initial gel strength and 10 minute gel strength measurements are not always indicative of gel

TABLE 4

GEL RATE CONSTANTS CALCULATED FROM FIGURE 5

Bentonite Per Cent	Sample #	Additives	Gel Strength (Ultimate)	Rate Constant
4.5	1	---------	34.4	0.047
5.5	2	---------	74.4	0.75
6.5	3	---------	114.	0.79
5.5	4	0.1% Na Tannate	104.	0.0089
5.5	5	Sodium Hydroxide	99.7	0.033

(From Gray, Darley and Rogers[18])

TABLE 5

CONSTANTS IN GELLING EQUATIONS OF BENTONITE SUSPENSIONS

Bentonite Per Cent	Gel Strength and Rate Constant	pH+ 9.2	pH+ 9.3-9.5	pH+ 9.9-10	pH+ 10.8-11
4.5	S'	34.4	40.1	48.5	69.6
4.5	k	0.047	0.071	0.076	0.063
5.5	S'	74.4	82.2	129.9	152.7
5.5	k	0.75	0.22	0.13	0.18
6.5	S'	114.	141.	250.	268.
6.5	k	0.79	0.30	0.10	0.25

(From Garrison[17])

TABLE 6

COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS, GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

	SAMPLE			
	Mud E	Mud F	Mud G No Treatment	Mud G 3 lb/bbl FCL
Weight, unstirred, lb/gal	11.0	10.7	10.6	
Weight, stirred, lb/gal	11.0	10.3	10.7	
Plastic Viscosity, cp	14	23	16	15
Yield Point, lb/100 sq ft	3	6	2	1
10-sec gel, lb/100 sq ft	1	2	1	0
10-min gel, lb/100 sq ft	8	8	7	3
API filtrate, ml	6.2	3.3	5.2	2.9
pH	10.9	10.6	10.5	10.4
Composition: Water % by vol	76	63	75	
Oil, % by vol	5	11	9	
Solids, % by vol	19	16	16	
Solids, % by wt	39	36	37	
Solids, SG	2.7	2.9	3.0	
Filtrate Ion Analysis:				
Chlorides ppm	3500	400	3000	
Sulfate, epm	250	300	130	
Carbonate, epm	24	28	12	
Bicarbonate, epm	12	160	12	
Calcium, epm	44	52	44	

Progressive Gel Strengths (lb/100 sq ft)	Temperature (°F)							
Time	75°	180°	75°	180°	75°	180°	75°	180°
0 minutes	1	1	2	2	1	1	0	0
3 minutes	2	3	2	5	3	8	1	1
10 minutes	8	18	8	12	7	26	3	3
30 minutes	15	40	11	18	17	58	5	5
60 minutes	27	90	18	16	29	91	6	6
2 hours	31	145	22	22	29	104	7	7
4 hours	37	190	29	42	46	172	10	10
8 hours	46	190	33	42				
16 hours	80	320	40	57	95	320	25	25

(From Weintritt and Hughes[19])

strength development which is observed at elevated temperatures and extended time. The trhee muds designated in table 6 were obtained from wells within the same field just prior to cementing operations.

Annis[20] noted that when a bentonite mud is quiescent, the gelling process depends on both temperature and time. Annis compared the effect of temperature on the initial and 30 minute gel strength of an 18 ppb bentonite suspension. Figure (12) indicates that the 30 minute gel strength of the 18 ppb suspension is at any temperature approximately six times the initial gel strength. the dependance of gel strength on time at different temperatures, as noted by Annis, is shown in figure (13). Based on these and other tests of up to 18 hours Annis concluded that there is a strong indication that gel strength increases indefinately with time.

In review, the above works indicate that the ultimate gel strength of water base muds is considerably higher than the values recorded for the initial and 10 minute gel strength. Although there is no direct relationship between gel strength and time it is possible, based on available information, to conclude that the ultimate gel strength of a mud will be several times larger than the initial or 10 minute gel strength of the mud. In reference to the work by Garrison,[17] it is possible to

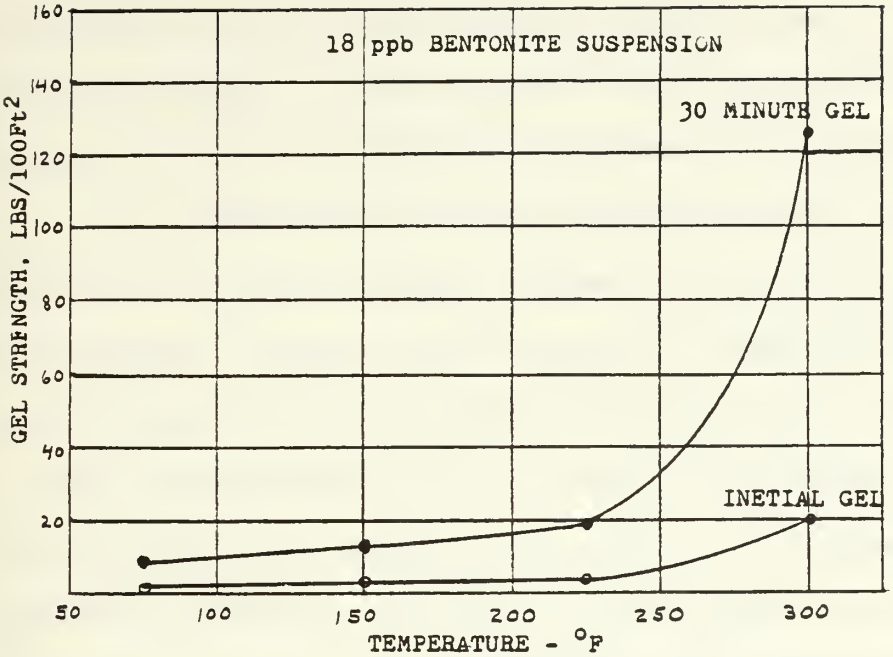

FIGURE 12. Effect of temperature on Initial and 30-Minute Gel Strengths (From Annis[20])

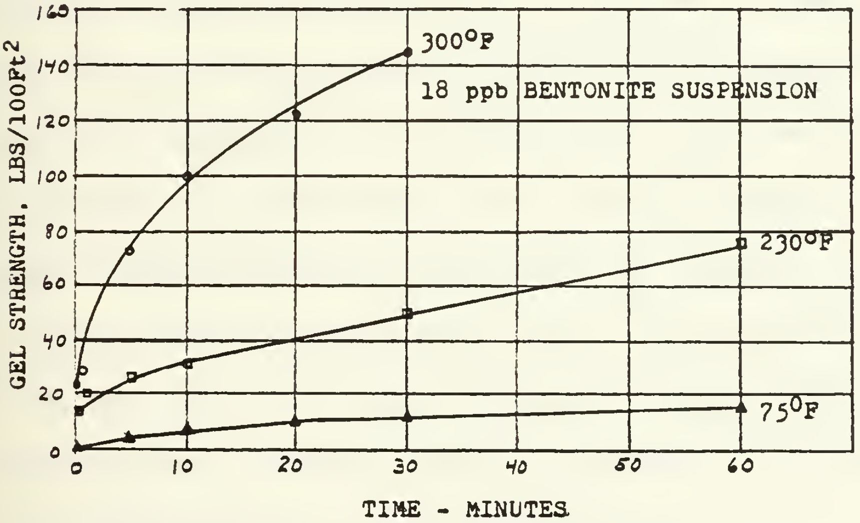

FIGURE 13. Effects of Time and Temperature on Gel Strength (From Annis[20])

consider the ultimate gel strength of a treated mud to be equivalent to that of a similar mud that was not treated, since the effect of the thinner is to decrease the rate of gelling and not the ultimate gel strength obtained.

In addition to time, temperature can have a major effect on the gel strength of water based drilling fluids. Srini-Vasan[21] studied the effects of temperature on the gel strength of several water based drilling muds. Table 7 lists the muds which were tested and figures (14), and (15) indicate the temperature verses gel strength relationships obtained. In most of the cases investigated by Srini-Vasan it was noted that the gel strength leveled off after 160°F. The emulsion and lime treated muds showed no change in gel strength with increase of temperature. It was found that each mud had its own characteristic curve and no quantitative interpretation was possible. The work of Weintritt and Hughes[16] as noted in table 6, indicates that emulsion mud G experienced no change in gel strength in going from 75 to 180°F over a wide range of times. It is noted that although the gel strength did not vary with temperature, it went from an initial gel strength of 0 to a gel strength of 25 after 16 hours.

The equipment utilized by Srini-Vasan restricted his investigation to temperatures up to 220°F. Annis[20] was capable of investigating the gel strenght up

TABLE 7

COMPOSITION OF THE MUD SAMPLES TESTED FOR GEL STRENGTH

SAMPLE NUMBER	COMPOSITION OF THE MUD**
33	2 per cent bentonite mud
34	3 per cent bentonite mud
35	4 per cent bentonite mud
39	10 lb/gal, 4 per cent bentonite, barite mud
43	10 lb/gal, 10 per cent (by volume) Diesel oil, 4 per cent bentonite, barite, emulsion mud
47	10 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud
49	10 lb/gal, low lime (1 lb/bbl) treated, 4 per cent bentonite, barite mud

---

** All muds referred to are water base muds. All per cent quantities mentioned denote weight per cents, unless other wise designated.

(From Srini-Vasan[21])

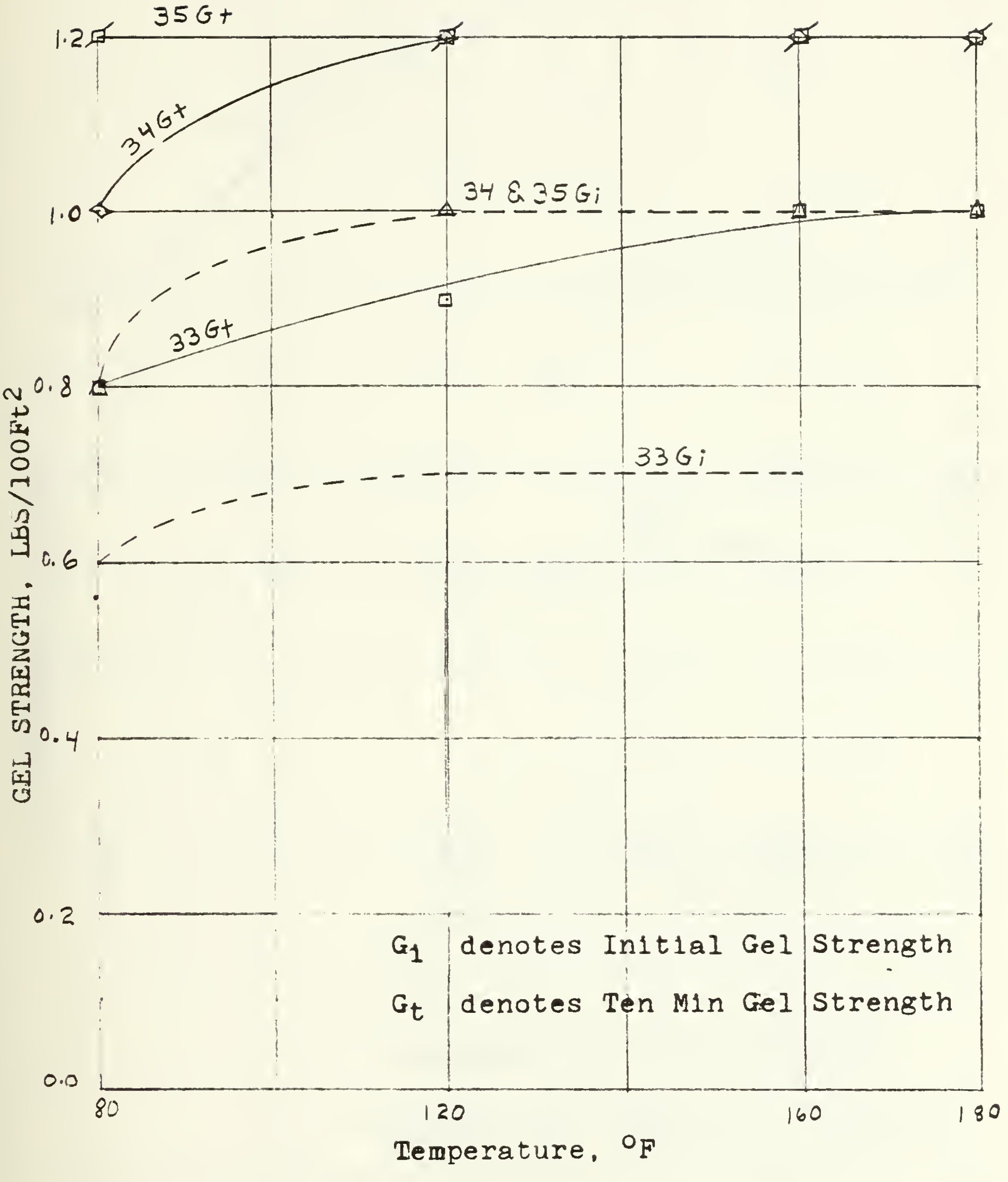

FIGURE 14. Gel Strength versus Temperature for Bentonite-water muds (From Srini-Vasan[21])

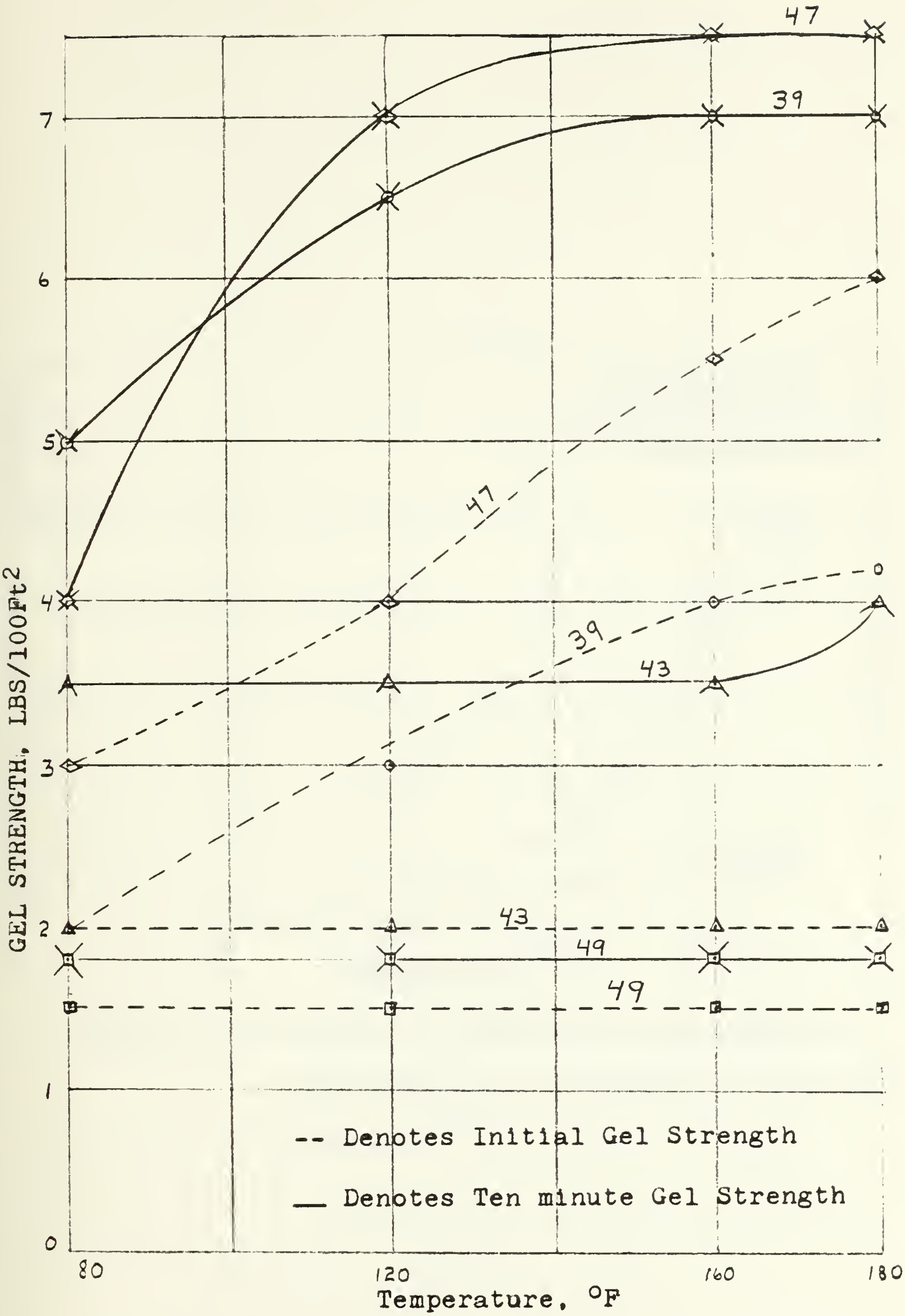

FIGURE 15. Gel Strength versus Temperature for different muds (From Srini-Vasan[21])

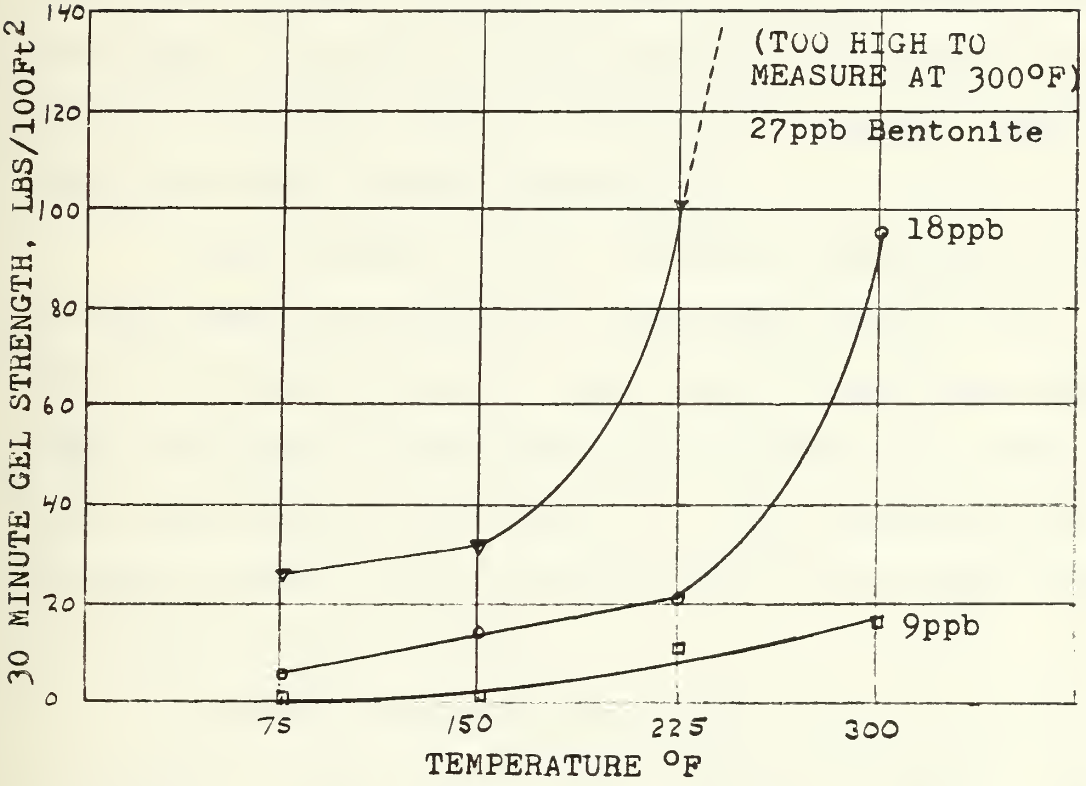

FIGURE 16. Effects of Temperature and Bentonite concentration on 30-Minute Gel Strength (From Annis[20])

to temperatures of 350°F. Srini-Vasan observed that the gel strengths leveled off after 160°F but Annis noted that at higher temperatures a rapid increase in the gel strength was noted. Figure (16) reflects this observation. Thus increased temperature, like increased bentonite concentration promotes flocculation. The temperature at which a rapid increase in gel strength occurs, represents the onset of flocculation. Therefore it is possible to expect the gel strength to increase significantly at some elevated temperature.

Annis studied the gel strength properties of about 40 water base field muds at temperatures ranging to 300°F. The muds covered a wide range of densities and mud types, although the majority were lignosulfonate muds. To draw conclusions on the effects of high temperature on gel strength the gel strength properties were averaged and are presented in figure (17).

Hiller[22] noted that some clay suspensions display a decrease in gel strength with increased pressure, especially at high temperatures. It was noted that the gel strength was reduced to 1/4 of its original value for a pressure increase from 300 to 8000 psi at a temperature of 302°F. This reduction in the gel strength resulting from increased pressure is presented in table 8.

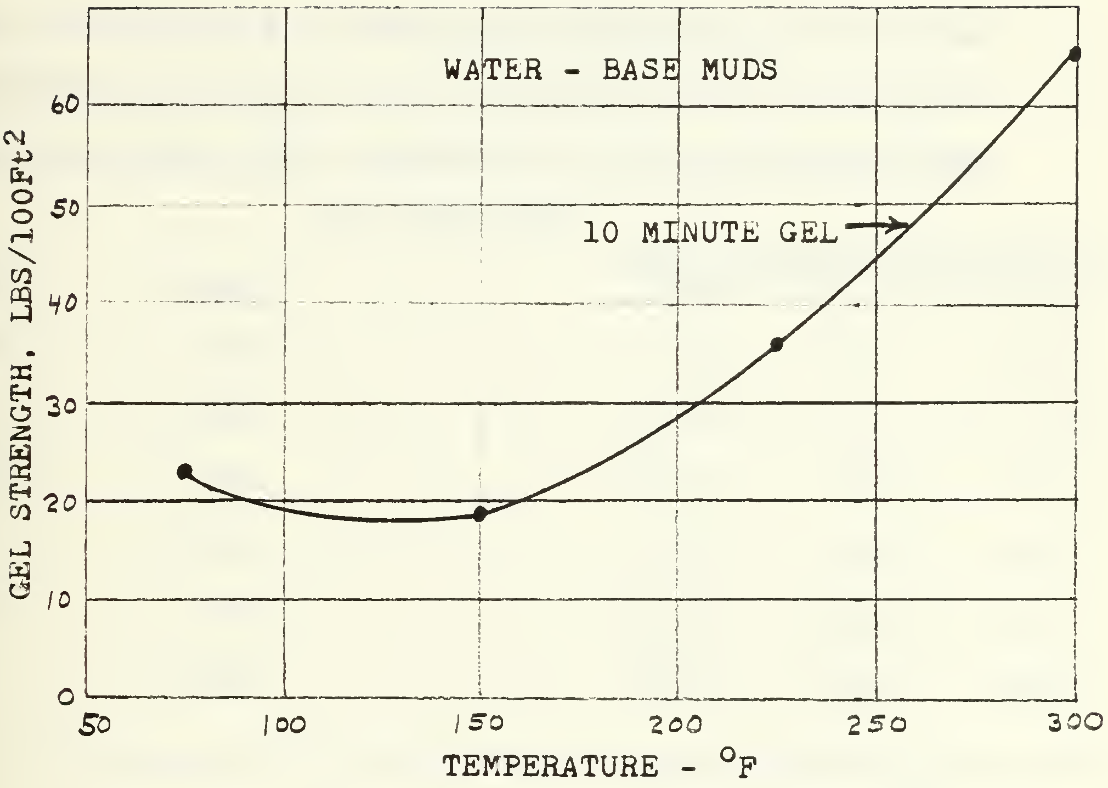

FIGURE 17. Effect of Temperature on 10-Minute Gel Strength (From Annis[20])

TABLE 8

GEL STRENGTH OF A 4 PER CENT SUSPENSION OF PURE SODIUM MONTMORILLONITE TO WHICH AN EXCESS OF 50 MEQ/LITER OF NaOH HAS BEEN ADDED, MEASURED AT VARIOUS TEMPERATURES AND PRESSURES.

		Gel Strength (lb/100sq ft)		
t(°F)	P(psi)	1 min	10 min	30 min
78	300	2.2	--	35.0
	8000	2.2	--	7.0
212	300	18.0	26.0	40.0
	8000	9.0	9.0	15.0
302	300	240.0	290.0	265.0
	8000	88.0	100.0	100.0

(From Hiller[22])

Although no direct means exists to determine the ultimate gel strength of a drilling mud at bore hole conditions, it is possible to safely say that the gel strength developed in the bore hole is considerable greater than that indicated by the initial and 10 minute gel strengths recorded for a given mud. The effects of time, temperature and pressure on the gel strength of the static mud column have been discussed above. In the range of pressures and temperatures normally encountered in disposal formations, pressure should exert a negligible effect on the gel strength. Flocculation at high temperature should not occur except in the deepest of disposal formations. Certain muds do not display a temperature dependance, but the effects of time is ever present.

The research discussed above investigated muds with 0 initial gel strength to ultimate gel strengths of 100'slbs/100SF. In an attempt to select a minimum ultimate gel strength that could be expected for the worst of mud and bore hole conditions, a value of 20 lbs/100 Ft^2 will be utilized for the ultimate gel strength in all gel strength pressure calculations in this report. This value will provide a considerable safety factor in most cases. The user of the procedure outlined in chapter III may utilize another value of the ultimate gel strength if available data allows such a determination.

The 20 lb/100Ft^2 ultimate gel strength was arbitrarily selected to insure that a sufficient safety factor is built into the proposed procedure. The selection is the result of individual judgment prejudiced by the above discussion.

APPENDIX E

EXAMPLE OF THE AREA OF REVIEW DETERMINATION PROCEDURE

Example of the Area of Review Determination Procedure

A chemical plant desires to initiate a new process at it's plant site located along the gulf coast of Texas. The new process will generate a continuous waste stream of 500 GPM for an estimated 20 years. The surface disposal capabilities of the plant are limited therefore the company desires to dispose of the new waste stream by subsurface injection. The proposed process will generate a chemical which is in high demand. To meet the demand the plant must operate without interruption, therefore the disposal system must be designed to provide continuous waste disposal for 20 years. The chemical company has employed a consultant to determine if it is feasible to dispose of the anticipated waste stream by subsurface injection. If the proposed injection is feasible, the company desires to know what the area of review will be so that its staff may begin to prepare the permit application and technical report.

Step 1

The consultant obtained all available well logs, formation water samples, core samples and other appropirate information from wells in the immediate area of the plant site. Utilizing the information obtained, the consultant preformed a hydrogeologic survey, conducted waste

and formation fluid compatibility tests, and assembled other information which indicated that a suitable injection formation existed at a depth of 5000 feet below the plant site. Table 9 presents the waste stream and injection formation properties determined by the consultant. The consultant selected a two well injection system to ensure continuous disposal capability.

The consultant determined that in addition to active wells there exists 126 abandoned wells within an approximate 2½ mile radius of the plant site.

Step 2

Figure (2) is a map of the relative positions of the abandoned wells with respect to the proposed injection wells at the plant site. The map has a grid system superimposed over it so that the relative distance, in feet between the abandoned wells and the injection wells can be determined.

Step 3

A two well injection system is selected to ensure that the disposal of the waste is not interrupted. Each well will inject at a rate of 250 GPM. Should a workover be required on a well, the other well will operate at 500 GPM until both wells are back on line. The well bore radius (r_w) of each well equals four inches. The wells will be operted for a period of 20 years.

TABLE 9

WASTE STREAM AND INJECTION FORMATION PROPERTIES

FORMATION PROPERTIES	DETERMINED VALUE
Porosity	.20
Depth to top of injection formation	5000 feet
Thickness	350 feet
Initial Pressure	2325 psi
Fracture Gradient	.68 psi/ft
Permeability	100 md

WASTE PROPERTIES	DETERMINED VALUE
Viscosity	.75 cp

COMBINED PROPERTIES	DETERMINED VALUE
Total Compressibility	.000005 1/psi

Information obtained in steps one and two is utilized to determine the gel strength and static mud column pressures. The pertinent information is presented in Table 1. A review of table 1 indicates that the minimun mud density recorded in the 126 abandoned wells is 9.4 lbs/gal. and the maximun bit diameter at the injection formation depth is 9.875 inches. These values are input into computer program INJWEL to calculate the static mud column and gel strength pressures, respectively. (See Appendix F). Table 10 represents the input required to calculate the formation, static mud column, and gel strength pressures and draw the X-Y Plot utilizing INJWEL. The injection rates are combined and it is assumed all the waste is being injected into well number one. Table 1 and Figure (3) represent the output and X-Y Plot, respectively that were generated by INJWEL. It is noted that the calculated area of review is approximately a radial distance of 7000 feet from the injection well.

Step 4

Utilizing information contained in tables 9 and 11 it is possible to calculate the formation pressure at a specified time at each of the abandoned wells. Table 12 represents the appropriate input to the computer program PRES to allow it to calculate the formation pressure at the abandoned wells and to draw an X-Y Plot of the area of

review. The pressure isobar drawn on the X-Y plot represents the static mud column plus gel strength pressure calculated by INJWEL. Table 13 and Figure (4) represent the output and X-Y Plot from PRES, respectively. Table 14 represents a listing of the abandoned wells determined to be located within the area of review.

Step 5

Since the minimum mud density (9.5 lbs/gal) found in the abandoned wells within the calculated area of review is greater than the 9.4 lbs/gal mud density utilized in the new calculations made in step three and the maximum bit diameter found in the abandoned wells within the area of review if 7.875 inches which is less than the 9.875 inches used in step three, INJWEEL will be rerun utilizing the above noted values. The gel strength plus a static mud colum pressure calculated with the new values for mud density and bit size is 2503.72 psi. This value replaces the old value and PRES is rerun to obtain the X-Y Plot of only the newly calculated area of review. Since the formation pressures do not change there is no need to recalculate them in PRES. Figures 5 and 6 represent the X-Y Plots of the area of review calculated by INJWEL and PRES, respectively. Table 5 lists the abandoned wells contained in the newly calculated area of review. A review of the table indicates that the mud density and bit diameter have both stabilized therefore the iterative pro-

TABLE 10

INPUT FOR COMPUTER PROGRAM INJWEL

```
20.00      5000.0     11.875
0.0        .75        1.0        100.    350.
2325.      20.0       .000005    .33
500.       9.4
```

TABLE 11

OUTPUT FROM FIRST RUN OF COMPUTER PROGRAM INJWEL

```
  20.000  5000.000     11.875
FRAC PRES FOR INJECTION FORMATION=      0.00


 2325.00        .75        1.00     100.00     350.00
     .20      20.00 .00000500          .33
PRES TO BREAK GEL STRENGTH=     28.04PSI


THE PRESSURE RESULTING FROM THE       9.40LBS/GAL MUD    COLUMN=   2444.00PSIA


THE COMBINED MUD COLUMN AND GEL STRENGTH PRESSURE=  2472.04


CONSTANT FLOW RATE=    500.00GAL/MIN


RADIUS    PRESSURE
      .33   2989.94
    10.00   2812.50
    20.00   2776.44
    30.00   2755.35
    40.00   2740.38
    50.00   2728.78
    60.00   2719.29
    70.00   2711.27
    80.00   2704.33
    90.00   2698.20
   100.00   2692.72
   200.00   2656.67
   300.00   2635.57
   400.00   2620.61
   500.00   2609.00
   600.00   2599.52
   700.00   2591.50
   800.00   2584.56
   900.00   2578.43
  1000.00   2572.95
  2000.00   2536.90
  3000.00   2515.81
  4000.00   2500.85
  5000.00   2489.25
  6000.00   2479.78
  7000.00   2471.78
  8000.00   2464.85
  9000.00   2458.74
 10000.00   2453.28
 11000.00   2448.34
 12000.00   2443.84
 13000.00   2439.70
```

TABLE 12

INPUT FOR COMPUTER PROGRAM PRES

```
       126          2          5          3          5
         1
0.20        350.0       4.0
0.75        .000005     2325.0     100.0      100.0      20.00
0.0         35000.      0.0        35000.
 4050.      15900.
 4700.      14550.
 5925.      18600.
 3375.      13275.
 7350.      15900.          13000.     7600.                    10100.     18650.
 6025.      17350.           8275.     6075.                    10175.     19850.
 7375.      14500.          11650.     6175.                    10150.     18400.
 4575.      18600.          12100.     4175.                    10825.     21000.
 7350.      17350.          12975.     6150.                    11100.     18350.
 8300.      17950.          14250.     4875.                    11200.     17150.
 7325.      20075.          16850.     1325.                    11325.     15975.
 1950.      14600.          16850.    31500.                    12225.     17750.
 2000.      13250.          19500.    31650.                    11425.     19600.
 6050.      14550.          18700.    31650.                    13325.     23125.
 1525.      16375.          19200.    30500.                    11700.     20750.
 6050.      21275.          19400.    31100.                    12250.     18700.
 4175.      20850.          18100.    31200.                    12450.     16500.
10800.      14300.          20600.    31550.                    10700.     17000.
 9600.      17550.          21750.    29700.                    13475.     15800.
10950.      12950.           7350.    28800.                    23300.     16250.
 3050.      17475.           9000.    29000.                    24050.     15475.
11825.      13650.          10750.    29400.                    21550.     14325.
 9350.      15100.          12200.    29750.               250.          15000.     16000.       0.0
12150.      12600.          12250.    31500.               250.          15500.     16500.       0.0
 9525.      13075.          13400.    29400.               (1982)
10450.      15600.          11250.    27650.                1.0
 8400.      11575.          11900.    28850.               (1986)
11225.      11400.          14100.    26600.                5.0
 9700.      11600.          15100.    26400.               (1991)
 6100.      11500.          17650.    26850.                10.0
 7250.      11500.          18025.    26700.               (1996)
 8750.      14000.          17700.    26075.                15.0
 9400.      16275.          17225.    25475.               (2001)
 8400.      12800.          16300.    27275.                20.0
 4675.      11475.          17200.    26200.                2472.
 3300.      11500.          19925.    28975.                           4
 6150.      12725.           5700.    28075.
 6100.      13225.           5325.    26600.
 8400.      16100.           6650.    26200.
 9825.      17100.           4725.    25325.
12700.      12450.           4525.    24375.
 3800.      10350.           5600.    25000.
 4850.       9875.           9625.    26825.
 4850.       8830.           7775.    25800.
 3550.       8775.           8450.    22775.
 6450.      10075.           6975.    22800.
 8525.      10050.          10875.    26400.
11200.      10500.          10450.    25025.
 5950.       7200.          11075.    23575.
 5800.       8800.          10775.    22700.
 9300.       8650.           9550.    22375.
 7325.       7075.          17000.    24750.
 8250.       8150.           7175.    21350.
 7150.       8650.           8000.    20675.
10650.       8375.           9200.    21675.
 9550.       7450.           8875.    20425.
```

TABLE 13

OUTPUT FROM COMPUTER PROGRAM PRES

```
WELL       WELL COORDINATES             FLOW RATES     INITIAL
 ID        X(FT)        Y(FT)           (GAL/MIN)     TIME(YRS)

 1       15000.00     16000.00           250.00          0.00

 2       15500.00     16500.00           250.00          0.00




FIELD DATA:            RESERVOIR                         FORMATION FLUID
              POROSITY      THICKNESS       VISCOSITY      COMPRESSIBILITY
              (FRAC.)        (FEET)           (CP)            1/(PSIA)

               .200          350.0            .750          .000005000


               INITIAL        FORMATION PERMEABILITY       WELL
              RESERVOIR          (MILLIDARCIES)           RADIUS
             PRES.(PSIA)      X-DIRECT       Y-DIRECT      (IN.)

              2325.00          100.0          100.0        4.00
```

TABLE 13 CONT

OBSERVATION POINT	PT. COORDINATES X(FT)	Y(FT)	BOTTOM HOLE PRESSURE(PSI) BY YEARS (1982)	(1986)	(1991)	(1996)	(2001)
1	4650.0	15900.0	2374.1	2413.5	2431.1	2441.4	2448.7
2	4700.0	14550.0	2373.8	2413.2	2430.7	2441.0	2448.[illegible]
3	5925.0	18600.0	2379.7	2418.4	2436.0	2446.3	2453.7
4	3375.0	13275.0	2367.5	2406.3	2423.8	2434.1	2441.4
5	7350.0	15900.0	2389.2	2428.4	2446.0	2456.3	2463.7
6	6025.0	17350.0	2380.4	2420.2	2437.8	2448.1	2455.4
7	7375.0	14500.0	2387.2	2427.4	2445.0	2455.3	2462.7
8	4575.0	18600.0	2372.7	2412.0	2429.5	2439.8	2447.1
9	7350.0	17350.0	2387.7	2427.9	2445.5	2455.9	2463.2
10	8300.0	17950.0	2393.0	2433.4	2451.1	2461.4	2468.8
11	7325.0	20075.0	2382.9	2422.9	2440.5	2450.8	2458.2
12	1950.0	14600.0	2363.4	2401.8	2419.2	2429.5	2436.8
13	2300.0	13250.0	2362.8	2401.1	2418.5	2428.8	2436.1
14	6050.0	14550.0	2380.1	2419.9	2437.4	2447.8	2455.1
15	1525.0	16375.0	2362.4	2400.6	2418.0	2428.3	2435.6
16	6050.0	21275.0	2374.6	2414.1	2431.6	2441.9	2449.3
17	4175.0	20850.0	2368.4	2407.3	2424.8	2435.1	2442.4
18	10800.0	14300.0	2412.4	2453.3	2471.0	2481.3	2488.7
19	9600.0	17550.0	2403.4	2444.1	2461.8	2472.1	2479.5
20	10950.0	12950.0	2406.9	2447.7	2465.4	2475.7	2483.1
21	3050.0	17475.0	2367.4	2406.3	2423.7	2434.0	2441.3
22	11825.0	13650.0	2418.6	2459.6	2477.3	2487.6	2495.0
23	9350.0	15100.0	2401.7	2442.3	2460.0	2470.4	2477.7
24	12150.0	12600.0	2413.2	2454.0	2471.7	2482.1	2489.5
25	9525.0	13075.0	2397.5	2438.0	2455.7	2466.0	2473.4
26	10450.0	15600.0	2412.5	2453.3	2471.0	2481.4	2488.8
27	8400.0	11575.0	2385.9	2426.0	2443.6	2453.9	2461.3
28	11225.0	11400.0	2399.4	2440.0	2457.6	2468.0	2475.4
29	9700.0	11600.0	2392.5	2432.9	2450.5	2460.9	2468.2
30	6000.0	11500.0	2375.1	2414.5	2432.1	2442.4	2449.7

TABLE 13 CONT

31	7250.0	11500.0	2380.3	2420.2	2437.7	2448.1	2455.4
32	8750.0	14000.0	2395.0	2435.5	2453.1	2463.5	2470.8
33	9400.0	16275.0	2403.0	2443.7	2461.4	2471.7	2479.1
34	8400.0	12800.0	2389.7	2430.0	2447.6	2457.9	2465.3
35	4675.0	11475.0	2370.0	2409.0	2426.5	2436.8	2444.1
36	3300.0	11500.0	2365.3	2403.9	2421.3	2431.6	2438.9
37	6150.0	12725.0	2378.1	2417.7	2435.3	2445.6	2453.0
38	6100.0	13225.0	2378.7	2418.4	2435.9	2446.3	2453.6
39	8400.0	16100.0	2395.2	2435.6	2453.3	2463.7	2471.0
40	9825.0	17100.0	2406.2	2446.9	2464.6	2474.9	2482.3
41	12700.0	12450.0	2415.5	2456.3	2474.1	2484.4	2491.8
42	3800.0	10350.0	2365.2	2403.8	2421.2	2431.5	2438.8
43	4850.0	9875.0	2367.7	2406.5	2424.0	2434.3	2441.6
44	4850.0	8800.0	2365.5	2404.2	2421.6	2431.8	2439.2
45	3550.0	8775.0	2361.9	2400.1	2417.4	2427.7	2435.0
46	6450.0	10075.0	2373.5	2412.9	2430.4	2440.7	2448.0
47	8525.0	10050.0	2381.2	2421.0	2438.6	2448.9	2456.3
48	11200.0	10500.0	2394.0	2434.4	2452.0	2462.4	2469.7
49	5950.0	7200.0	2364.9	2403.4	2420.9	2431.1	2438.4
50	5800.0	8800.0	2369.3	2407.2	2424.7	2435.0	2442.3
51	9300.0	8650.0	2378.6	2418.3	2435.9	2446.2	2453.5
52	7325.0	7075.0	2368.0	2406.8	2424.3	2434.6	2441.9
53	8250.0	8150.0	2373.7	2413.1	2430.6	2440.9	2448.2
54	7150.0	8650.0	2372.0	2411.2	2428.7	2439.0	2446.4
55	10650.0	8375.0	2381.3	2421.2	2438.8	2449.1	2456.4
56	9550.0	7450.0	2374.7	2414.1	2431.7	2442.0	2449.3
57	13400.0	7600.0	2382.3	2422.2	2439.8	2450.1	2457.4
58	8275.0	6075.0	2367.2	2406.0	2423.4	2433.7	2441.0
59	11650.0	6175.0	2373.7	2413.1	2430.6	2440.9	2448.3
60	12100.0	4175.0	2366.6	2405.4	2422.8	2433.1	2440.4
61	12975.0	6150.0	2375.3	2414.8	2432.3	2442.6	2449.9

TABLE 13 CONT

62	14250.0	4875.0	2373.7	2409.8	2427.3	2437.6	2444.9
63	16850.0	1325.0	2358.5	2396.2	2413.5	2423.7	2431.0
64	16850.0	31500.0	2357.6	2395.1	2412.4	2422.6	2429.9
65	19500.0	31650.0	2355.9	2393.1	2410.4	2420.6	2427.9
66	18700.0	31650.0	2356.4	2393.7	2411.0	2421.2	2428.5
67	19200.0	30500.0	2359.1	2396.9	2414.3	2424.5	2431.8
68	19400.0	31100.0	2357.3	2394.9	2412.1	2422.4	2429.7
69	18100.0	31200.0	2357.9	2395.5	2412.8	2423.0	2430.3
70	20600.0	31550.0	2355.3	2392.4	2409.6	2419.8	2427.1
71	21750.0	29700.0	2358.7	2396.4	2413.7	2424.0	2431.3
72	7350.0	28800.0	2359.0	2396.8	2414.1	2424.3	2431.6
73	9000.0	29900.0	2358.5	2396.2	2413.5	2423.7	2431.0
74	10750.0	29400.0	2361.8	2400.0	2417.4	2427.6	2434.9
75	12200.0	29750.0	2362.0	2400.2	2417.6	2427.8	2435.1
76	12250.0	31500.0	2357.0	2394.5	2411.7	2422.0	2429.2
77	13400.0	29400.0	2363.8	2402.3	2419.7	2429.9	2437.2
78	11250.0	27650.0	2368.1	2407.0	2424.4	2434.7	2442.0
79	11900.0	28850.0	2364.6	2403.2	2420.6	2430.9	2438.2
80	14100.0	26600.0	2375.0	2414.4	2432.0	2442.3	2449.6
81	15100.0	26400.0	2376.2	2415.7	2433.3	2443.6	2450.9
82	17650.0	26850.0	2373.0	2412.3	2429.8	2440.1	2447.5
83	18025.0	26700.0	2373.2	2412.6	2430.1	2440.4	2447.7
84	17700.0	26075.0	2376.3	2415.9	2433.4	2443.7	2451.1
85	17225.0	25475.0	2379.7	2419.4	2437.0	2447.3	2454.7
86	16300.0	27275.0	2372.1	2411.4	2428.9	2439.2	2446.5
87	17200.0	26200.0	2376.2	2415.8	2433.3	2443.7	2451.0
88	19925.0	28975.0	2362.9	2401.3	2418.6	2428.9	2436.2
89	5700.0	28075.0	2357.9	2395.6	2412.8	2423.1	2430.4
90	5325.0	26600.0	2360.4	2398.4	2415.8	2426.0	2433.3
91	6650.0	26200.0	2364.2	2402.7	2420.1	2430.4	2437.7
92	4725.0	25325.0	2361.8	2400.0	2417.4	2427.6	2434.9

TABLE 13 CONT

93	4525.0	24375.0	2363.2	2401.6	2419.0	2429.2	2436.6
94	5600.0	25000.0	2364.7	2403.2	2420.6	2430.9	2438.2
95	9625.0	26825.0	2368.5	2407.4	2424.9	2435.2	2442.5
96	7775.0	25800.0	2367.9	2406.8	2424.2	2434.5	2441.8
97	8450.0	22775.0	2379.7	2419.4	2437.0	2447.3	2454.7
98	6975.0	22800.0	2374.3	2413.8	2431.3	2441.6	2448.9
99	10875.0	26400.0	2372.2	2411.4	2428.9	2439.2	2446.6
100	10450.0	25025.0	2376.8	2416.5	2434.0	2444.3	2451.7
101	11075.0	23575.0	2385.0	2425.1	2442.7	2453.0	2460.4
102	10775.0	22700.0	2388.5	2428.7	2446.3	2456.7	2464.0
103	9550.0	22375.0	2385.4	2425.5	2443.1	2453.4	2460.7
104	17000.0	24750.0	2383.7	2423.7	2441.3	2451.6	2458.9
105	7175.0	21350.0	2379.0	2418.8	2436.3	2446.7	2454.0
106	8000.0	20675.0	2384.6	2424.7	2442.3	2452.6	2460.0
107	9200.0	21675.0	2386.8	2426.9	2444.6	2454.9	2462.2
108	8875.0	20425.0	2389.9	2430.2	2447.8	2458.2	2465.5
109	10100.0	18650.0	2404.4	2445.1	2462.8	2473.1	2480.5
110	10175.0	19850.0	2399.9	2440.5	2458.1	2468.[illegible]	2475.9
111	10150.0	18400.0	2405.7	2446.4	2464.1	2474.5	2481.8
112	10825.0	21000.0	2397.8	2438.3	2456.0	2466.3	2473.7
113	11100.0	18350.0	2414.4	2455.3	2473.0	2483.3	2490.7
114	11200.0	17150.0	2424.2	2461.1	2478.9	2489.2	2496.6
115	11325.0	15975.0	2423.0	2464.0	2481.7	2492.0	2499.4
116	12225.0	17750.0	2430.5	2471.5	2489.2	2499.6	2507.0
117	11425.0	19600.0	2409.9	2450.7	2468.4	2478.8	2486.1
118	13325.0	20125.0	2418.0	2458.9	2476.6	2487.0	2494.4
119	11700.0	20750.0	2404.0	2444.6	2462.3	2472.7	2480.0
120	12250.0	18700.0	2423.5	2464.5	2482.2	2492.6	2500.0
121	12450.0	16500.0	2440.0	2481.0	2498.8	2509.2	2516.5
122	10700.0	17000.0	2414.9	2455.8	2473.5	2483.8	2491.2
123	13475.0	15800.0	2462.3	2503.5	2521.2	2531.6	2539.0

TABLE 13 CONT

124	23300.0	16250.0	2387.3	2427.5	2445.1	2455.4	2462.8
125	24450.0	15475.0	2382.8	2422.7	2440.3	2450.7	2458.0
126	21550.0	14325.0	2397.1	2437.6	2455.3	2465.6	2473.0

TABLE 14

WELLS CONTAINED IN THE AREA OF REVIEW

WELL	X-CORD	Y-CORD	Mud Den (lb/gal)	Bit Size (in)
18	10800	14300	12.9	6.75
19	9600	17550	10.6	7.875
20	10950	12950	12.5	7.875
22	11825	13650	12.4	7.875
23	9350	15200	10.7	7.875
24	12150	12600	12.7	7.875
25	9525	13075	11.5	7.875
26	10450	15600	10.1	7.875
28	11225	11400	10.4	8.75
33	9400	16275	9.7	7.875
40	9825	17100	9.5	7.875
41	12700	12450	13.4	7.875
109	10100	18650	10.9	7.875
110	10175	19850	11.1	7.875
111	10150	18400	11.0	7.875
112	10825	21000	10.5	7.875
113	11100	18350	10.5	7.875
114	11200	17150	11.6	7.875
115	11325	15975	11.5	7.875
116	12225	17750	11.0	7.875
117	11425	19600	11.1	7.875
118	13325	20125	11.2	7.875
119	11700	20750	9.7	7.875
120	12250	18700	9.7	7.875
121	12450	16500	9.5	7.875
122	10700	17000	9.7	7.875
123	13475	15800	11.6	7.875
126	21550	14325	10.2	7.875

cedure need not be repeated. The area of review calculated by this second iteration is the true area of review for the proposed injection operation.

Step 6

Since step five defined the true area of review for the proposed injection operation it is now necessary to evaluate each well listed in table 15 on an individual basis. Utilizing the mud density and bit size for each well listed in the table the static mud column and gel strength pressure, respectively are calculated at each well. The sum of the pressures at each well is compared with the formation pressure calculated at the well by PRES, Table 13. If the combined gel strength and static mud column pressure is less than the formation fluid pressure corrective action must be considered at the well in question. Corrective action could be avoided by reducing the injecting rate or by relocating the injectors to modify the area of review so that the critical well no longer presents a problem. If the gel strength pressure plus static mud column pressure exceeds the formation pressure the well in question will not pose a pollution threat to fresh water.

Step 7

Table 16 lists the wells located within the true area of review. These wells need to be reviewed on an individual basis to determine which wells need corrective action utilizing the criteria established by the TDWR.

TABLE 15

WELLS CONTAINED IN THE TRUE AREA OF REVIEW

WELL #	X-CORD	Y-CORD	MUD DEN	BIT SIZE
116	12225	17750	11.0	7.875
121	12450	16500	9.5	7.875
123	13475	15800	11.6	7.875

TABLE 16

WELLS REQUIRING INDIVIDUAL REVIEW FOR POSSIBLE CORRECTIVE ACTION

WELL #	Static Mud Column Pres (psi)		Gel Strength Pressure (psi)		Combined Pressure (psi)	Formation Pressure (psi)
116	11.0(5000)(.052)	+	33.72	=	2893.72	2507.0
*121	9.5(5000)(.052)	+	33.72	=	2503.72	2516.5
123	11.6(5000)(.052)	+	33.72	=	3049.72	2539.0

*Well 121 is the only well which requires actual investigation to determine if corrective action is required. If well 121 is properly plugged no further action is required, if not it requires corrective action.

APPENDIX F

COMPUTER PROGRAM INJWEL

```
      PROGRAM INJWEL(INPUT,OUTPUT,PLOTR)
C
C      THE PURPOSE OF THE FOLLOWING PROGRAM IS TO:
C
C      DETERMINE AN AREA OF REVIEW AROUND A SINGLE INJECTION
C      WELL BY COMPARING THE FORMATION PRESSURE CONE OF THE
C      INJECTOR WITH THE SUM OF:
C      (1) THE PRESSURE REQUIRED TO BREAK THE GEL STRENGTH OF
C      MUD FOUND IN THE ABANDONED WELLS WITHIN THE VICINITY
C      (2 1/2 MILE RADIUS) OF THE INJECTOR
C      (2) THE HYDROSTATIC PRESSURE OF THE MUD COLUMN IN THE
C      ABANDONED WELLS WITHIN THE VICINITY
C
C      THE RESERVOIR IS ASSUMED TO BE ISOTROPHIC, HOMOGENEOUS,
C      HORIZONTAL AND INFINATE IN AREAL EXTENT.  GRAVITY EFFECTS
C      ARE ASSUMED NEGLIGIBLE.  THE FLUID WITHIN THE RESERVOIR
C      IS CONSIDERED TO HAVE A SMALL AND CONSTANT COMPRESSIBILITY.
C
C      CALCULATIONS OF THE PRESSURE REQUIRED TO BREAK THE MUD
C      GEL STRENGTH ASSUME:  THE ABANDONED WELL DIAMETER USED
C      IS THE LARGEST ABANDONED WELL DIAMETER IN THE VICINITY
C      OF THE INJECTOR, THE GEL STRENGTH USED IS THE ONE HOUR
C      GEL STRENGTH OF THE MUD USED TO DRILL THE VICINITY WELLS,
C      THE HEIGHT OF THE MUD COLUMN IN THE ABANDONED WELLS CAN
C      BE MEASURED  AND THE LOWEST MEASURED VALUE IS USED, AND
C      ALL WELLS WERE ABANDONED WITHOUT LONG STRING CASING.
C
C      CALCULATIONS OF THE PRESSURE REQUIRED TO OVERCOME THE
C      HYDROSTATIC MUD COLUMN PRESSURE ASSUME THAT THE MUD
C      DENSITY IS UNIFORM THROUGHOUT THE HEIGHT OF THE
C      ABANDONED WELL BORE AND THAT THE MUD OCCUPIES THE ENTIRE
C      WELL BORE HEIGHT
C
C      INPUT DATA FOR THE PROGRAM IS DESCRIBED AS FOLLOWS:
C
C      VARIABLE     UNIT          DESCRIPTION
C
C
C      GELSTR       LBS/100SF     GEL STRENGTH OF MUD IN
C                                 ABANDONED WELLS
C      HMUD         FEET          LOWEST HEIGHT OF THE MUD COLUMNS
C                                 IN THE ABANDONED WELLS
C      DABDW        INCHES        LARGEST DIAMETER OF THE ABANDONED
C                                 WELLS IN THE VICINITY
C      PFRAC        PSIA          FRACTURE PRESSURE OF INJECTION
C                                 FORMATION
C      PINIT        PSIA          INITIAL INJECTON FORMATION PRESSURE
C      VISC         CENTIIPOISE   FLUID VISCOSITY
C      B            RES VOL/      RESERVOIR FLUID FORMATION VOLUME
C                   SURFACE VOL   FACTOR
C      PERM         MILIDARCIES   PERMEABILITY
C      H            FEET          FORMATION THICKNESS
C      PHI          FRACTION      FORMATION POROSITY
C      TLIFE        YEARS         LIFE OF THE INJECTON WELL
C      C            1/PSIA        FLUID COMPRESSIBILITY
C      RW           FEET          WELL BORE RADIUS
C      QCONST       GAL/MIN       CONST MAX FLOW RATE OF WASTE
C                                 INJECTED INTO THE INJECTION
C                                 FORMATION
C      RHO          LBS/GAL       ABANDONED WELL MUD DENSITY
C
```

```
C
C
C      INPUT OATA CAROS FOR THE PROGRAM ARE AS FOLLOWS:
C
C      CARO   VARIABLE NAMES             FORMAT
C
C       1     GELSTR,HMUO,OABOW          (3F10.2)
C       2     *PFRAC                     (3F10,2)
C       3     PINIT,VISC.B.PERM,H        (5F10.2)
C       4     PHI,TLIFE.C.RW             (2F10.0.F10.8,2F10.2)
C       5     *QCONST,RHO                (2F10.0)
C
C      *IF IT IS OESIREO TO RUN THE PROGRAM TO OETERMINE THE
C      MAXIMUN FLOW RATE ALLOWABLE FOR A SPECIFIED FRACTURE
C      PRESSURE,LET PFRAC=THE SPECIFIEO FRACTURE PRESSURE
C      ANO QCONST=0.0
C      IF IT IS DESIRED TO RUN THE PROGRAM FOR AN INPUT
C      CONSTANT MAXIMUN FLOW RATE, LET PFRAC=0.0 ANO
C      QCONST=THE DESIRED FLOW RATE
C
C
      DIMENSION PATRAO(50),RADIUS(50),PGELBW(50),PCOMBO(50),PCOLMN(50)
      DIMENSION PLIMITS(50)
      READ 10,GELSTR,HMUD,DABOW
      PRINT 10,GELSTR,HMUD,DABOW
   10 FORMAT(3F10.3)
      READ 10,PFRAC
      PRINT 11,PFRAC
   11 FORMAT(1X,*FRAC PRES FOR INJECTION FORMATION=*,F10.2//)
      READ 12,PINIT,VISC.B.PERM,H
      PRINT 12,PINIT,VISC.B,PERM.H
   12 FORMAT(5F10.2)
      READ 13,PHI,TLIFE,C,RW
      PRINT13,PHI,TLIFE,C,RW
   13 FORMAT(2F10.2,F10.8,F10.2)
      PDELTA=(3.33E-03*GELSTR*HMUD)/OABDW
      PGEL=PDELTA
      PRINT 21,PGEL
   21 FORMAT(1X,*PRES TO BREAK GEL STRENGTH=*,F10.2,*PSI*,//)
      READ 14,QCONST,RHO
   14 FORMAT(2F10.2)
      PCOLM=0.052*RHO*HMUO
      PRINT 17,RHO,PCOLM
   17 FORMAT(1X,*THE PRESSURE RESULTING FROM THE*,F10.2,*LBS/GAL MUO
     *COLUMN=*,F10.2,*PSIA*//)
      PCOMB=PCOLM+PDELTA
      PRINT 18,PCOMB
   18 FORMAT(1X,*THE COMBINED MUD COLUMN ANO GEL STRENGTH PRESSURE=*,
     *F10.2//)
      RW=RW*30.5
      CC=C*14.7
      PERMC=PERM/1000
      PINITC=PINIT/14.7
      PFRACC=PFRAC/14.7
      HC=H*30.5
      TLIFEC=TLIFE*31536000
      PIE=3.14156
      IF(PFRAC.LE.0.0) GO TO 15
      AR=(PHI*VISC*CC*(RW**2))/(4*PERMC*TLIFEC)
      QMAXC=((PINITC-PFRACC)*4*PIE*PERMC*HC)/(VISC*B*(EIX(AR)))
      QMAX=QMAXC*.0158
      PRINT 22,QMAX
```

```
22 FORMAT(1X,*TO PREVENT FRACTURING, THE MAXIMUN FLOW RATE ALLOWABL
  *E FOR THE*,F10.2,*YEAR LIFE OF THE INJECTION WELL=*,F10.2//)
   IF (PFRAC.GT.0.0) GO TO 25
15 PRINT 16,QCONST
16 FORMAT(1X,*CONSTANT FLOW RATE=*,F10.2,*GAL/MIN*//)
   QMAX=QCONST
   QMAXC=QMAX/.0158
   AR=(PHI*VISC*CC*(RW**2))/(4*PERMC*TLIFEC)
25 PATRW=PINITC-(((VISC*8)/(4*PIE*PERMC*HC))*QMAXC*(EIX(AR)))
   PATRW=PATRW*14.7
   RW=RW/30.5
   PRINT 23,RW,PATRW
23 FORMAT(1X,*RADIUS    PRESSURE*,/2F10.2)
   I=1
   RADIUS(I)=10.
   DO 30 I=1,31
   AR=(PHI*VISC*CC*((30.5*RADIUS(I))**2))/(4*PERMC*TLIFEC)
   PATRAD(I)=PINITC-(((VISC*8)/(4*PIE*PERMC*HC))*QMAXC*(EIX(AR)))
   PATRAD(I)=PATRAD(I)*14.7
   PRINT 24,RADIUS(I),PATRAD(I)
24 FORMAT(2F10.2)
   IF(RADIUS(I).GE.1000.) GO TO 32
   IF(RADIUS(I).GE.100.) GO TO 31
   RADIUS(I+1)=RADIUS(I)+10.
   IF(RADIUS(I).LT.100.) GO TO 30
31 RADIUS(I+1)=RADIUS(I)+100.
   IF(RADIUS(I).LT.1000.) GO TO 30
32 RADIUS(I+1)=RADIUS(I)+1000.
30 CONTINUE
   DO 33 I=1,31
   PCOLMN(I)=0.052*RHO*HMUD
   PCOMBD(I)=PCOLMN(I)+PDELTA
33 CONTINUE
   I=1
   PLIMITS(I)=PINIT
   I=2
   PLIMITS(I)=PATRW
   CALL PLOTS(0,0,5LPLOTR)
   CALL SCALE(RADIUS,13.,31,1)
   CALL AXIS(2.0,1.5,34HRADIAL DISTANCE FROM INJECTOR (FT),
  *-34,13.,0.,RADIUS(32),RADIUS(33))
   CALL SCALE(PLIMITS,8.,2,1)
   PATRAD(32)=PLIMITS(3)
   PATRAD(33)=PLIMITS(4)
   PCOMBD(32)=PLIMITS(3)
   PCOMBD(33)=PLIMITS(4)
   PCOLMN(32)=PLIMITS(3)
   PCOLMN(33)=PLIMITS(4)
   CALL AXIS(2.0,1.5,24HFORMATION PRESSURE(PSIA),
  *24,8.,90.,PATRAD(32),PATRAD(33))
   CALL ORIGIN(2.0,1.5,0)
   CALL LINE(RADIUS,PATRAD,31,1,6,14)
   CALL LINE(RADIUS,PCOMBD,31,1,6,10)
   CALL LINE(RADIUS,PCOLMN,31,1,6,4)
   CALL SHADE(3,0.6)
   CALL SYMBOL(2.0,7.9,0.5,22HAREA(RADIUS) OF REVIEW,0.,22)
   CALL SYMBOL(1.0,7.6,0.2,14,0.,-1)
   CALL SYMBOL(1.3,7.5,.2,28HWELL LIFE FORMATION PRESSURE,0.,28)
   CALL SYMBOL(1.0,7.1,0.2,4,0.,-1)
   CALL SYMBOL(1.3,7.0,0.2,26HSTATIC MUD COLUMN PRESSURE,0.,26)
   CALL SYMBOL(1.0,6.6,0.2,10,0.,-1)
   CALL SYMBOL(1.3,6.5,0.2,24HCOMBINED SMCP AND GEL ST,0.,24)
```

```
 CALL SYMBOL(8.0,7.5,.2,5HINPUT,0.,5)
 CALL SYMBOL(8.0,7.3,.10,25HGEL STRFNGTH(LB/100SF) = ,0.,25)
 CALL NUMBER(999.,999.,.10,GELSTR,0.,2)
 CALL SYMBOL(8.0,7.1,.10,
*32HABANDONED WELL MUD HEIGHT(FT) = ,0.,32)
 CALL NUMBER(999.,999.,.10,HMUD,0.,2)
 CALL SYMBOL(8.0,6.9,.10,30HABANDONED WELL DIAMETER(IN) = ,
*0.,30)
 CALL NUMBER(999.,999.,.10,DABDW,0.,3)
 CALL SYMBOL(8.0,6.7,.10,
*37H*FORMATION FRACTURF PRESSURE(PSIA) = ,0.,37)
 CALL NUMBER(999.,999.,.10,PFRAC,0.,2)
 CALL SYMBOL(8.0,6.5,.10,
*35HINITIAL FORMATION PRESSURE(PSIA) = ,0.,35)
 CALL NUMBER(999.,999.,.10,PINIT,0.,2)
 CALL SYMBOL(8.0,6.3,,10,24HVISCOSITY(CENTIPOISE) = ,0.,24)
 CALL NUMBER(999.,999.,.10,VISC,0.,2)
 CALL SYMBOL(8.0,6.1,.10,
*39HFLUID FORMATION VOLUME FACTOR(RV/SV) = ,0.,39)
 CALL NUMBER(999.,999.,.10,B,0.,2)
 CALL SYMBOL(8.0,5.9,.10,29HPERMEABILITY(MILLIDARCIES) = ,0.,29)
 CALL NUMBER(999.,999.,.10,PERM,0.,2)
 CALL SYMBOL(8.0,5.7,.10,26HFORMATION THICKNESS(FT) = ,0.,26)
 CALL NUMBER(999.,999.,.10,H,0.,2)
 CALL SYMBOL(8.0,5.5,.10,
*21HPOROSITY(FRACTION) = ,0.,21)
 CALL NUMBER(999.,999.,.10,PHI,0.,2)
 CALL SYMBOL(8.0,5.3,.10,
*36HLIFE OF THE INJECTION WELL(YEARS) = ,0..36)
 CALL NUMBER(999.,999.,.10,TLIFE,0.,2)
 CALL SYMBOL(8.0,5.1,.10,
*32HFLUID COMPRESSIBILITY(1/PSIA) = ,0.,32)
 CALL NUMBER(999.,999.,.10,C,0.,8)
 CALL SYMBOL(8.0,4.9,.10,
*33HINJECTION WELL BORE RADIUS(FT) = ,0.,33)
 CALL NUMBER(999.,999.,.10,RW,0.,2)
 CALL SYMBOL(8.0,4.7,.10,
*38HMAXIMUN CONSTANT FLOW RATE(GAL/MIN) = ,0.,38)
 CALL NUMBER(999.,999.,.10,QMAX,0.,2)
 CALL SYMBOL(8.0,4.5,.10,
*38HABANDONED WELL MUD DENSITY(LBS/GAL) = ,0.,38)
 CALL NUMBER(999.,999.,.10,RHO,0.,2)
 CALL SYMBOL(8.0,4.3,.10,
*36H*IF THE FRACTURE PRESSURE=0, THEN A ,0..36)
 CALL SYMBOL(8.0,4.1,.10,
*36HSTATED MAX FLOW RATE, RATHER THAN A ,0.,36)
 CALL SYMBOL(8.0,3.9,.10,
*34HMAX FLOW RATE CALCULATED FROM THE ,0.,34)
 CALL SYMBOL(8.0,3.7,.10,27HFRACTURE PRESSURE WAS USED ,0.,27)
 CALL SYMBOL(8.0,3.5,,18,6HOUTPUT,0.,6)
 CALL SYMBOL(8.0,3.3,.10,
*41HPRESSURE AT THE WELL BORE RADIUS(PSIA) = ,0.,41)
 CALL NUMBER(999.,999.,.10,PATRW,0.,2)
 CALL SYMBOL(8.0,3.1,.10,
*30HGEL STRENGTH PRESSURE(PSIA) = ,0.,30)
 CALL NUMBER(999.,999.,.10,PGEL,0.,2)
 CALL SYMBOL(8.0,2.9,.10,
*35HSTATIC MUD COLUMN PRESSURE(PSIA) = ,0.,35)
 CALL NUMBER(999.,999.,.10,PCOLM,0.,2)
 CALL SYMBOL(8.0,2.7,.10,
*33HCOMBINED SMCP AND GEL ST(PSIA) = ,0.,33)
 CALL NUMBER(999.,999.,.10,PCOMB,0.,2)
```

```
      CALL PLOT(13.,8.,999)
      STOP
      END
      FUNCTION EIX(ARG)
      IF (ARG.GT.2.) GO TO 2
      IF(ARG.LE.0.01) GO TO 3
      N=12
      IF (ARG.LT.1.) N=8
      F=1.0
      XO=1.0
      EIX=ALOG(ARG)+.577215665
      N1=N-1
      DO 1 I=1,N1
      F=F*I
      XO=-ARG*XO
      EIX=EIX+XO/(F*I)
1     CONTINUE
      EIX=EIX-ARG*XO/(F*N*(N+1.34))
      RETURN
2     XO=EXP(-ARG)
      EIX=ARG+6./(1.+3./ARG)
      I=5
4     EIX=ARG+I/(1.+I/EIX)
      I=I-1
      IF (I.LE.0) GO TO 5
      GO TO 4
5     EIX=-XO/EIX
      RETURN
3     EIX=ALOG(ARG)+.577215665-ARG+ARG*ARG/4.
      RETURN
      END
```

APPENDIX G

COMPUTER PROGRAM PRES

```
      PROGRAM PRES(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,PLOTR)
C  THE PURPOSE OF THE FOLLOWING PROGRAM IS TO:
C
C  (1)  SOLVE FOR RESEVOIR PRESSURES AT GIVEN DISTANCES AND TIMES
C
C  (2)  CALCULATE AND PLOT ISOBARS
C
C
C  THE RESERVOIR IS ASSUMED TO BE ANISOTROPIC, HOMOGENEOUS, INFINITE
C  AND IN AN UNSTEADY STATE FLOW.  THE FLUID WITHIN THE RESERVOIR
C  IS CONSIDERED TO BE SLIGHTLY COMPRESSIBLE.
C
C  FOR FORMULA DERIVATION AND BACKGROUND INFORMATION REFER TO:
C
C  CAUDLE,DR.BEN H., FUNDAMENTALS OF RESERVOIR ENGINEERING,
C       SOCIETY OF PETROLEUM ENGINEERING OF AIME (AMERICAN
C       INSTITUTE OF MINING, METALLURGICAL, AND PETROLEUM
C       ENGINEERS,INC., DALLAS,TEXAS, 1967.
C
C  SINCE DATA INPUT IS THE ONLY NECESSARY REQUIREMENT FOR THE
C  FUNCTIONING OF THE PROGRAM, IT WILL BE DESCRIBED AS FOLLOWS:
C
C
C  VARIABLE:                UNIT:                 DESCRIPTION:
C
C  N                    .   DIMENSIONLESS(DL)     NUMBER OF LOCATIONS FOR
C                                                 PRESSURE CALCULATIONS
C
C  M                        DL                    NUMBER OF WELLS
C
C  NTCHG                    DL                    NUMBER OF TIME CHANGES
C                                                 FOR PRESSURE CALCULATIONS
C
C  NCALC                    DL                    CODED VARIABLE THAT
C                                                 DETERMINES THE SUBJECT
C                                                 AREA TO BE CALCULATED
C
C  NYRP                     DL                    NUMBER OF YEAR PERIODS
C                                                 FOR PRESSURE CALCULATIONS
C
C  NIBAR                    DL                    NUMBER OF ISOBAR PLOTS
C
C  PHI                      FRACTION              FORMATION POROSITY
C
C  H                        FEET                  FORMATION THICKNESS
C
C  RW                       INCHES                WELL RADIUS
C
C
C  VISC                     CENTIPOISE            FLUID VISCOSITY
C
C  C                        1/(PSIA)              FLUID COMPRESSIBILITY
C
C  PINIT                    PSIA                  INITIAL RESERVOIR
C                                                 PRESSURE
C
C  XK,YK                    MILLIDARCIES          PERMEABILITY IN XAY
C                                                 DIRECTIONS
C
C  YRPLOT                   YEARS                 TIME PERIOD FOR ISOBAR
```

```
C                                                  PLOT
C
C   FXMIN,FXMAX              FEET                  FIELD MIN. & MAX. LIMITS
C                                                  IN X DIRECTION OF PLOT
C
C   FYMIN,FYMAX              FEET                  FIELD MIN. & MAX. LIMITS
C                                                  IN Y DIRECTION OF PLOT
C
C   XINC,YINC                FEET                  X AND Y INCREMENTS ON
C                                                  ISOBAR PLOT
C
C   X(I),Y(I)                FEET                  X.Y LOCATION OF
C                                                  PRESSURE CALCULATIONS
C
C   Q(J)                     GAL/MIN               FLOW RATE OF WELL (J)
C
C   XW(J),YW(J)              FEET                  X.Y LOCATION OF WELLS
C
C   T(J)                     YEARS                 INITIAL TIME OF
C                                                  (PRODUCTION/INJECTION)
C
C   YR(J)                    YEARS                 SPECIFIED YEAR FOR
C                                                  PRESSURE CALCULATIONS
C
C   YRINC(J)                 YEAR                  YEAR INCREMENTS BETWEEN
C                                                  SPECIFIED YEARS
C
C   PRBAR(K)                 PSIA                  NIBAR NUMBER OF
C                                                  PRESSURES FOR ISOBAR
C                                                  PLOTS
C
C   ISYM(K)                  DL                    SYMBOL USED FOR
C                                                  CORRESPONDING PRESSURE
C                                                  ON ISOBAR PLOT
C                                                  *=11,+=3,X=4
C
C
C   THE PRECEDING VARIABLES ARE INPUTTED INTO THE COMPUTER EACH TIME THE
C   FLOW OF THE PROGRAM CROSSES A READ STATEMENT.  FOR EACH READ
C   STATEMENT A DATA CARD SHOULD BE READ.
C
C   CARD#      VARIABLE NAMES              FORMAT          #READS
C   1          N,M,NTCHG,NCALC,NYRP           (8I10)      C  1
C   2          NIBAR                          (8I10)         1
C   3          PHI,H,RW,                      (8F10.0)       1
C   4          VISC,C,PINIT,XK,YK,YRPLOT      (8F10.0)       1
C   5          FXMIN,FXMAX,FYMIN,FYMAX        (8F10.0)       1
C   6          X(I),Y(I)                      (8F10.0)       N
C   7          Q(J),XW(J),YW(J),T(J)          (8F10.0)       M
C   8          YR(J)                          (10A6)         NYRP
C   9         YRINC(J)                      (8F9.0)       NYRP
C   10         PRBAR(K)                       (8F10.0)       NIBAR
C   11         ISYM(K)                        (8I10)         NIBAR
C
C   WARNINGS:
C   (1)  ALWAYS USE INPUT DATA WITH CORRECT UNITS.  SEE ABOVE
C   (2)  INJECTION WELLS MUST BE INPUTTED BEFORE PRODUCTION
C        WELLS REGARDLESS OF WHEN THE WELLS BEGAN OPERATING
C   (3)  OSCILLATION OF PLOT AROUND WELL BORES MAY BE ELLIMINATED BY
C        INCREASING VARIABLE RW
C   (4)  EXCESSIVE RUN TIME OF PROGRAM MAY BE REDUCED BY:
C        A. INCREASING THE VARIABLE DFCT WITHIN THE DATA STATEMENT
```

```
C        B. INCREASING THE XINC AND YINC INCREMENT VALUES WITHIN THE
C           ISOBAR PLOT
C   (5)  THE PLOT ROUTINE WITHIN THIS PROGRAM IS SUBJECT TO CHANGE
C        ACCORDING TO USER.  THUS, THE PROGRAM WILL BE SLIGHTLY
C        ALTERED WITH EACH USER TO CONFORM TO THE LIMITATIONS AND
C        RESTRICTIONS OF EACH PLOT ROUTINE
C   (6)  IF THE ISOBAR PLOT SHOULD BE BLANK, THE PRESSURES DEFINING
C        THE ISOBARS DO NOT EXIST WITHIN THE FIELD
C   NOTE:
C   (1)  SET NCALC EQUAL TO THE FOLLOWING NUMBERS TO CALCULATE THE
C        SPECIFIED SECTIONS OF THE PROGRAM
C
C        NCALC=
C               1...PRESSURE CALCUATION ONLY
C               2...ISOBAR PLOT ONLY
C               3...ISOBAR PLOT AND PRESSURE CALCULATION
C   (2)  WELLS WITH VARYING FLOW RATES WITH TIME MAY BE USED BY SUPER-
C        IMPOSING THE DIFFERENTIAL ON THE PREVIOUS FLOW RATE
C
      COMMON T(100),XW(1000),YW(1000),XK,YK,H,PHI,Q(100),VISC,C,NTOTW
      DIMENSION X(200),Y(200),XF(1000),YF(1000),XX(10000),YY(10000),
     1FYRMX(15),YR(10),YRINC(15),PRES1(20),PRBAR(10),ISYM(10)
C
C   INPUT DATA SECTION
C
      DATA PI,CF1,CF2,EPS,VCON,DFCT,TCONV,XINC,YINC/3.140,13474811.76.30
     1022.01,1.0E-10,0.002228,0.1,31536000.0,400.0,400.0/
      READ(5,9)N,M,NTCHG,NCALC,NYRP
      READ(5,9)NIBAR
      READ(5,5) PHI,H,RW
      READ(5,5)VISC,C,PINIT,XK,YK,YRPLOT
      READ(5,5)FXMIN,FXMAX,FYMIN,FYMAX
       DO 10 I=1,N
       READ(5,5)X(I),Y(I)
 10    CONTINUE
      WRITE(6,70)
      WRITE(6,71)
      WRITE(6,72)
      WRITE(6,73)PHI,H,VISC,C
      WRITE(6,74)
      WRITE(6,76)
      WRITE(6,77)
      WRITE(6,78)PINIT,XK,YK,RW
      WRITE(6,47)
      WRITE(6,48)
      NI=0
      NPW=0
       DO 15 J=1,M
       READ(5,5) Q(J),XW(J),YW(J),T(J)
       IF(Q(J).GT.0.0) NI=NI+1
       IF(Q(J).LT.0.0) NPW=NPW+1
       WRITE(6,49) J,XW(J),YW(J),Q(J),T(J)
       T(J)= T(J)*TCONV
 15    CONTINUE
       DO 23 J=1,NYRP
       READ(5,11)YR(J)
       READ(5,5)YRINC(J)
 23    CONTINUE
       DO 39 K=1,NIBAR
       READ(5,5)PRBAR(K)
       READ(5,9)ISYM(K)
 39    CONTINUE
```

```
      IF(NCALC.EQ.2)GO TO 38
C
C  PRESSURE CALCULATIONS
C
      WRITE(6,50)
      WRITE(6,51)
      WRITE(6,52) (YR(J).J=1,NYRP)
       DO 35 I=1,N
       WRITE(6,60)I,X(I).Y(I)
       DO 30 II=1,NYRP
       TSEC=TCONV*YRINC(II)
       SUM=0.
       DO 25 J=1,M
       IF (TSEC-T(J).LE.0.) GO TO 25
       STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
       FINEI=(((X(I)-XW(J))**2)/XK)+(((Y(I)-YW(J))**2)/YK)
       IF(FINEI.LT.EPS) GO TO 30
       X1=STEI*FINEI
       CALL EIX(X1,FUNC)
       SUM=(FUNC*Q(J))+ SUM
 25    CONTINUE
       AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
       HALF=AP*SUM
       PRES1(II) = PINIT+HALF
 30    CONTINUE
       WRITE(6,61) (PRES1(II),II=1,NYRP)
 35    CONTINUE
      IF(NCALC.EQ.1)GO TO 555
C
C  PRESSURE CALCULATIONS FOR ISOBAR PLOT
C
 38   CONTINUE
      RW=(RW/12.)+4.5
      NTOTW=NPW+NI
      CALL PLOTS(0,0,SLPLOTR)
      CALL DRWPAO(FXMIN,FXMAX,FYMIN,FYMAX)
      CALL SKETCH(XW,YW,M,14,0)
      CALL SKETCH(X,Y,N,1,0)
      CALL SYMBOL(3.0,10,1.0.3,14HAREA OF REVIEW.0.,14)
      CALL SYMBOL(7.0,10,05,.10,14,0.,-1)
      CALL SYMBOL(7.2,10.0,.10,24HINJECTION WELL LOCATIONS,0.,24)
      CALL SYMBOL(7.0,9,9,.10,1,0.,-1)
      CALL SYMBOL(7.2,9,85..10.24HABANOONED WELL LOCATIONS.0.,24)
      CALL SYMBOL(7.0,9.75..10,4,0.,-1)
      CALL SYMBOL(7.2,9.7,.10,30HSTATIC MUO COLUMN+GEL STRENGTH,0.,30)
      CALL SYMBOL(7.2,9.55..10.23HPRESSURE(PSI) ISOBAR = ,0.,23)
      CALL NUMBER(999.,999.,.10,PRBAR,0.,2)
      DO 301 J=1,NTOTW
      XTEST=ABS(FXMIN-XW(J))
      YTEST=ABS(FYMIN-YW(J))
      IF(((XTEST**2)+(YTEST**2)).LE.(RW**2)) FXMIN=FXMIN+RW
 301  CONTINUE
       DO 300 K=1,NIBAR
       XP=FXMIN
       YP=FYMIN
       TSEC=TCONV*YRPLOT
 323   CONTINUE
       SUM=0.0
       DO 302 J=1,M
       IF(TSEC-T(J).LE.0.) GO TO 302
       STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
       FINEI=(((XP-XW(J))**2)/XK)+(((YP-YW(J))**2)/YK)
```

```
      IF(FINEI.LT.EPS) GO TO 303
      X1=STEI*FINEI
      CALL EIX(X1,FUNC)
      SUM=(FUNC*Q(J))+ SUM
302   CONTINUE
      AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
      HALF=AP*SUM
      PRESP=PINIT+HALF
303   CONTINUE
      XPOLD=XP
      XP= XP+XINC
      IF((XP.GT.FXMAX).AND.(YP.GT.FYMAX))GO TO 400
      IF(XP.GT.FXMAX)GO TO 304
      DO 305 J=1,M
     IF((((XP-XW(J))**2)+((YP-YW(J))**2)).LE.(RW**2)) GO TO 303
305   CONTINUE
      SUM=0.0
      DO 306 J=1,M
      IF(TSEC-T(J).LE.0.)GO TO 306
      STEI=(PHI*VISC*C*CF1)/(4.0*(TSEC-T(J)))
      FINEI=(((XP-XW(J))**2)/XK)+(((YP-YW(J))**2)/YK)
      IF(FINEI.LT.EPS) GO TO 312
      X1=STEI*FINEI
      CALL EIX(X1,FUNC)
      SUM=(FUNC*Q(J))+SUM
306   CONTINUE
      AP=(VISC*CF2)/(4.0*PI*((XK*YK)**.5)*H)
      HALF=AP*SUM
      PROLD=PRESP
      PRESP=PINIT+HALF
312   CONTINUE
      IF((PROLD.LT.PRBAR(K)).AND.(PRESP.GT.PRBAR(K))) GO TO 307
      IF((PROLD.GT.PRBAR(K)).AND.(PRESP.LT.PRBAR(K))) GO TO 307
      GO TO 303
307   CONTINUE
      PDIF1=ABS(PRBAR(K)-PROLD)
      PDIF2=ABS(PRESP-PPOLD)
      XP=(((XP-XPOLD)*PDIF1)/(PDIF2)) + XPOLD
      CALL SKETCH(XP,YP.1,ISYM(K),1)
      GO TO 303
304   CONTINUE
      YP= YP+YINC
      XP=FXMIN
      GO TO 323
400   CONTINUE
300   CONTINUE
     CALL PLOT(0.0,0.0,999)
555  CONTINUE
5    FORMAT(8F10.0)
9    FORMAT(8I10)
11   FORMAT(10A6)
47   FORMAT(59H1 WELL       WELL COORDINATES          FLOW RATES     INIT
    1IAL)
48   FORMAT(60H   ID          X(FT)      Y(FT)          (GAL/MIN)      TIME(
    1YRS))
49   FORMAT(/,1X,I3,6X,F9.2,3X,F9.2,7X,F6.2,5X,F9.2)
50   FORMAT(73H1 OBSERVATION   PT. COORDINATES          BOTTOM HOLE PRESS
    1URE(PSI) BY YEARS)
51   FORMAT(29H    POINT       X(FT)     Y(FT))
52   FORMAT(1H+,33X,1A6.4X,1A6,4X,1A6,4X,1A6,4X.1A6)
60   FORMAT(/,3X,I3,6X,F8.1,1X,F9.1)
61   FORMAT(1H+,33X,F6.1,4X,F6.1,4X,F6.1,4X,F6.1,4X,F6.1)
```

```
 70  FORMAT(671 FIELD OATA:                RESERVOIR                     FORM
    1ATION FLUID)
 71   FORMAT(74H                       POROSITY      THICKNESS      VISCOSITY
    1    COMPRESSIBILITY)
 72   FORMAT(70H                       (FRAC.)        (FEET)          (CP)
    1        1/(PSIA))
 73   FORMAT(/,18X,F5.3,9X,F5.1,8X,F6.3,10X,F10.9)
 74   FORMAT(//,65H0                        INITIAL        FORMATION PERMEARILI
    1TY         WELL)
 76   FORMAT(66H                       RESERVOIR         (MILLIDARCIES)
    1     RADIUS)
 77   FORMAT(66H                      PRES.(PSIA)       X-OIRECT      Y-DIRECT
    1       (IN.))
 78   FORMAT(/,18X,F8.2,7X,F7.1,6X,F7.1,7X,F5.2)
      STOP
      END

      SUBROUTINE EIX(X,XEI)
C
C  SUBROUTINE TO CALCULATE THE EXPONENTIAL INTEGRAL USING THE
C  INFINITE SERIES METHOO
C
      DATA EPHS,GAMMA/1.E-10,0.5772156649/
      XEI=-GAMMA-ALOG(X)
      I=0
 8    I=I+1
      FACT=1.
       DO 6 J=1,I
       XJ=J
 6     FACT= FACT*XJ
      XI=I
      FNEG=-1.0
      TERM=((FNEG)**(I+1))*((X**I)/(XI*FACT))
      XEI=XEI+TERM
      IF (TERM.LT.0.0) TERM=-TERM
      IF (TERM.LT.EPHS) GO TO 7
      GO TO 8
 7    CONTINUE
      RETURN
      END
```

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VITA

Stephen Eugene Barker was born in Norwich, New York, on November 8, 1950, the son of Jacke Marie Barker and Stuart Harold Barker. After completing his work at New Berlin Central High School, New Berlin, New York, in 1968, he entered the United States Army. Upon discharge from the Army in 1973, he entered the State University of New York College at Oneonta, New York. He received the degree of Bachelor of Science from State University College at Onenota in December, 1976. In September, 1976 he entered the State University of New York at Buffalo, New York. He received the Bachelor of Science in Engineering from the University of Buffalo in September, 1977. Commissioned an Ensign in the United States Navy in July, 1977, he presently holds the rank of Lieutenant. Married to the former Holly Edwards of New Berlin, New York, they have three childres: Brie Alexandra (May, 1978) Wesley Adam (October 1980) and Eric Christian (October, 1980). In January, 1981, he entered the Graduate School of the University of Texas.

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